The Nachtlichter app: a citizen science tool for documenting outdoor light sources in public spaces

Andrea Gokus[1], Andreas Hänel[2], Andreas Ruby[3], Arne Dröge-Rothaar[4], Brita Küchly[2], Christopher C.M. Kyba[3,4*], Daniel Fischer[2], David Gruber[5], Eva C. Weiß[2], Friederike Klan[6], Georg Sulzer[2], Georgia T. MacMillan[7], Helga Küchly[3], Henning von Brandis[2], Isabell C. Wuthenow[8], Jacob Koglin[2], Janina Mattern[2], Johannes A. Schultz[4], Johannes Veh[9], Katharina Leiter[10], Loeka L. Jongejans[4,3], Marcus Langejahn[11], Maria Zschorn[2], Marijana Pavić[12] , Maximilian Blaschke[13], Melanie Brauchler[14], Michaela Leipold[8], Nathalie Küppers[15], Nona Schulte-Römer[3,16], Normän Naboulsi[2], Petra Bilela[12], Reinhart Binder[2], René Curwy[2], Sabine Frank[17], Sebastian Falkner[2], Sicco Bauer[2], Steffen Liese[13], Swantje Maurer[4], Tamara Rom[12], Thomas Kunzemann[2], Vita Tičinović[12], Yiğit Öner Altıntaş[3]

[1]Washington University in St. Louis, 63130 St. Louis, MO, USA
[2]Citizen Scientist
[3]GFZ German Research Centre for Geosciences, 14467 Potsdam, Germany
[4]Ruhr-Universität Bochum, 44801 Bochum, Germany
[5]Naturmuseum Südtirol, 39100 Bozen, Italy
[6]Deutsches Zentrum für Luft- und Raumfahrt, 07745 Jena, Germany
[7]University of Galway, Galway, Ireland
[8]Umweltzentrum Fulda, 36041 Fulda, Germany
[9]Erlangen National High Performance Computing Center, 91058 Erlangen, Germany
[10]Planetarium Nürnberg, 90429 Nürnberg, Germany
[11]Technische Universität München
[12]University of Split, 21000 Split, Croatia
[13]Umweltinstitut Leipzig e.V., 04277 Leipzig, Germany
[14]Universität Trier, 54286 Trier, Germany
[15]Hochschule Bochum, 44801 Bochum, Germany
[16]Humboldt-Universität zu Berlin, 10117 Berlin, Germany
[17]Landkreis Fulda, 36037 Fulda, Germany

* Kyba C, Tel.: +49-331-288-28973.
E-mail address: kyba@gfz-potsdam.de

*Corresponding Author: C Kyba (kyba@gfz-potsdam.de)

Abstract

The relationship between satellite based measurements of city radiance at night and the numbers and types of physical lights installed on the ground is not well understood. Here we present the “Nachtlichter app”, which was developed to enable citizen scientists to classify and count light sources along street segments over large spatial scales. The project and app were co-designed: citizen scientists played key roles in the app development, testing, and recruitment, as well as in analysis of the data. In addition to describing the app itself and the data format, we provide a general overview of the project, including training materials, data cleaning, and the result of some basic data consistency checks.

Keywords: Citizen Science, Lighting Inventory, Light Pollution, Nachtlicht-BüHNE, Outdoor lighting

1. Introduction

Satellite images of the artificial lights of Earth at Night have fascinated people since their first development by Sullivan (1989, Fig. 1). Since that time, satellite data has documented how light emissions continued to grow globally through the final decade of the 20th century and first two decades of the 21st (Kyba et al., 2017; Sánchez de Miguel, Bennie, et al., 2021). These images, however, do not tell us about what kinds of light sources or lighting applications are responsible for the light emissions, and consequently they provide only limited information about what types of lighting applications are responsible for the growth. Consider the “Altstadt” and “Neustadt” of Dresden, Germany (Fig. 2), as viewed by the Visible Infrared Imaging Radiometer Suite Day-Night Band (DNB) (Miller et al., 2013; Elvidge et al., 2021). Both of these are dense urban areas, but the Altstadt is several times brighter than the Neustadt. Why is this? Does the Altstadt have more streets, or brighter streets, or are the lights unshielded, or are there more lit advertisements? And how many lights per square kilometer are needed to produce a radiance of 1 nW/cm^2sr as sensed by that satellite? This is important information for planning and evaluating the transition to sustainable lighting, but unfortunately these questions cannot be answered by satellite data alone.

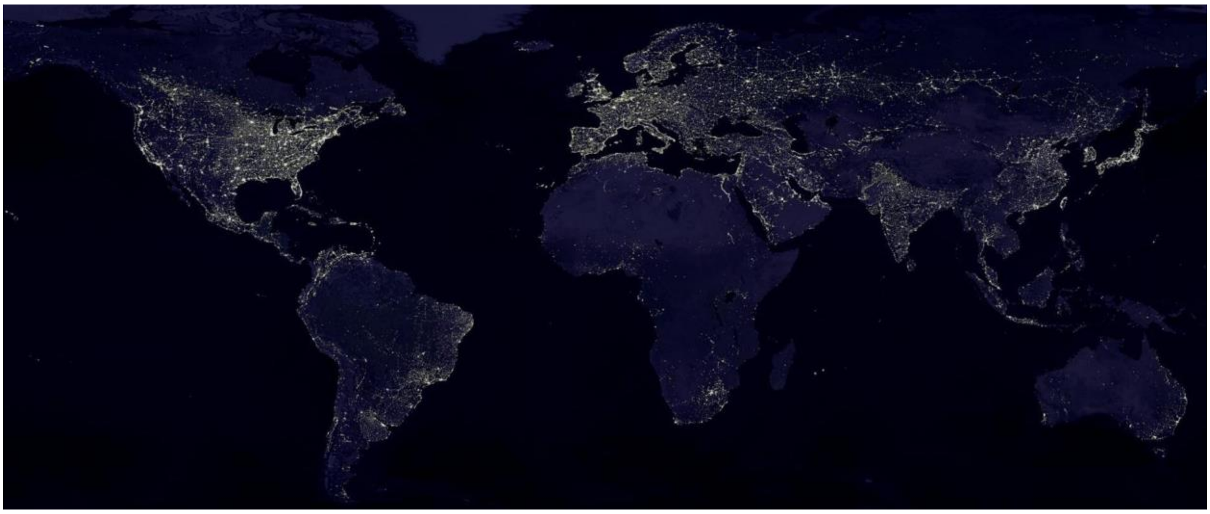

Fig. 1. Composite image of parts of the Earth at Night produced by NASA based on Defense Meteorological Program Operational Line-Scan System data from the Earth Observation Group (Elvidge et al., 2021).

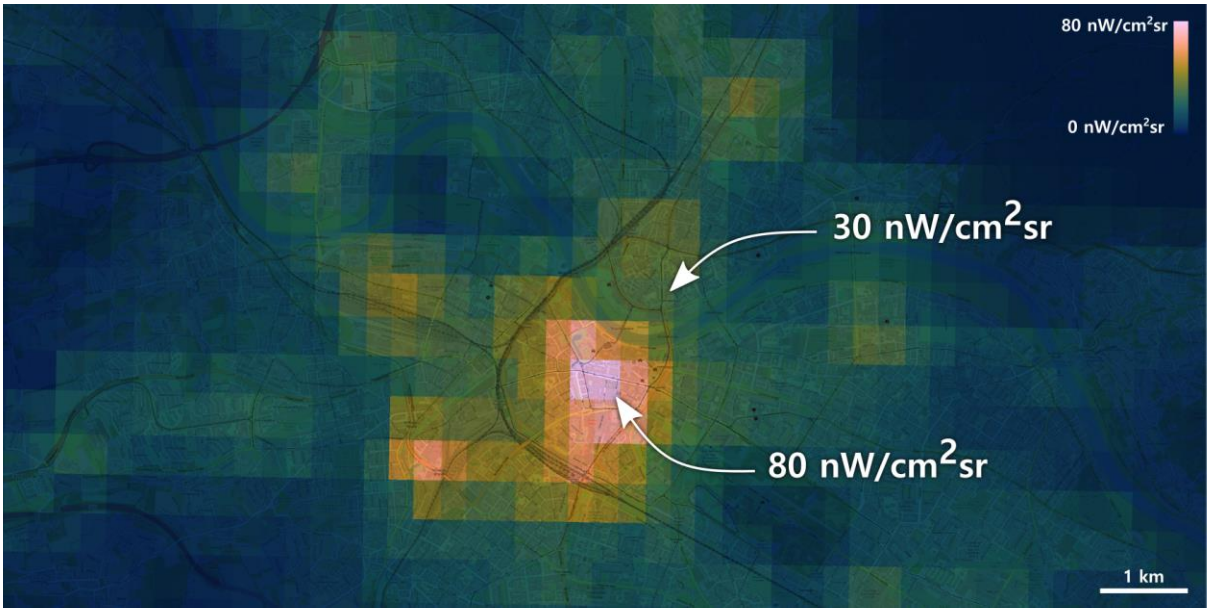

Fig. 2. Radiance from areas near Dresden, Germany during September, 2020 as viewed by the DNB satellite radiometer. The "Altstadt" area is several times brighter than the "Neustadt" area although both are urban areas. Image produced using Google Earth Engine. Background map data copyright OpenStreetMap contributors and available from https://www.openstreetmap.org.

In many communities, authorities have detailed lighting cadasters which contain geographic information about light sources, such as the luminaire positions, technology installed, styles, and wattages. These cadasters are however generally limited to the light sources under public control, such as streetlights and pathway lighting, whereas much (or most) of the light in illuminated spaces actually comes from private actors. This could be for example from a business owner who uses illuminated signs, or a homeowner who installs decorative lighting. Light also escapes unintentionally from the windows of private houses and workplaces, and is often intentionally radiated from behind shop windows for advertising purposes. In order to understand light emissions from urban areas, including public and private lights, and how these emissions contribute to light pollution in the form of skyglow, more complete lighting inventories are needed. This paper describes the *Nachtlichter* ("Night lights") app, which we developed to allow citizen scientists (Eitzel et al., 2017) to conduct large-scale and comprehensive lighting inventories. Within our citizen science methodology, project participants (who need no prior experience with lighting) are recruited from many different cities, and trained to make consistent classifications. This makes it possible to obtain observations over much larger areas than an individual research team could.

Before explaining the app, it is useful to briefly discuss some of the previous work that has been done in this area. The results from several studies that examined relative contributions of light emissions to either upward light or skyglow are summarized in Table 1. The earliest work we are aware of comes from the Second World War. The US government undertook a detailed study to understand what types of light sources were responsible for skyglow (Cleaver, 1943), as they had determined that German U-boats were targeting merchant ships based on their dark silhouettes against the artificial sky brightness of the US Eastern Seaboard. Studies have since taken different approaches to arrive at these numbers, including imaging (e.g. (Kuechly et al., 2012)), looking at how skyglow changes in response to a lighting change (Hiscocks & Gudmundsson, 2010), or a combination of the two (Bará et al., 2018).

Table 1. Summary of studies that have examined the contribution of different types of lights to skyglow, satellite data, or total light emissions. Values are not listed when a category was not included in the study. The different groups used different lighting categories, considered different times of night and community sizes, and in some cases consisted of multiple observations. Here we have attempted to combine these observations into similar categories for comparison purposes. Because of this, we recommend readers to refer to the direct sources and do not re-cite these values in future publications.

Study	Commercial lighting	Street lighting	Headlights	Industrial/ Institutional	Indoor / residential	Other / Rest	Place
Cleaver (1943)	38%	33%	15%		8%	6% (defense)	Point Pleasant; Jacksonville Beach, USA
Luginbuhl et al. (2009)	36%	8%	4%	11%	9%	32% (sports)	Flagstaff, Arizona, USA
Hiscocks & Gudmundsson (2010)		50%				50%	Reykjavik, Iceland
Kuechly et al. (2012)	23%	33%		26%	10%	7%	Berlin, Germany
Ruhtz et al. (2015)		25%		18%		57%	Upper Austria, Austria
Wuchterl & Reithofer (2017)	33%	33%				33%	Vienna, Austria
Bará et al. (2018)		67%	5%	6%	22%		A Coruña, Spain; Arteixo, Spain
Barentine et al. (2020)		8%				92%	Tucson, Arizona, USA
Hänel & Kunzemann (2021)		40-60%				40-60%	Preussisch-Oldendorf; Fulda, Germany
Kyba et al. (2021)		16% urban 35% rural				84% urban 65% rural	Tucson, Arizona, USA; Köditz & Königsee, Germany
Bará et al. (2023)		75% (before) 45% (after)				25% (before) 55% (after)	Ribeira, Spain
Walczak et al. (2023)	21%	24%		10%	35%	11%	Indianapolis, USA

The large differences here are likely related both to the different natures of each of the studies, as well as differences between the communities studied. This shows that there is a research gap regarding both how lighting practice changes along an urban-rural gradient, as well as from one city to another. Our Nachtlichter app was developed to address these questions, as well as the earlier question of how different types of light contribute to the radiance observed from space. A Nachtlichter app observation consists of a count and classification of every individual light source that can be seen while walking along a given transect (typically from one street corner to the next). This paper describes the entire research process in detail, from how we co-designed the project with a core team of citizen scientists and ran dedicated data acquisition campaigns, to the structure of the app data. Readers interested primarily in understanding the data may wish to skip most of the paper, and concentrate on the subsections dealing with the definition of the light type categories (2.2), the data structure (4.1), data quality (6.1), and methodological limitations (6.3).

2. Co-Development of the Nachtlichter Project

The Nachtlichter app is one of two co-designed apps developed within the larger Nachtlicht-BüHNE project (***Bü****rger-***H***elmholtz-***Ne***tzwerk für die* ***E****rforschung nächtlicher Lichtphänomene* / Citizen-Helmholtz Network for research on night light phenomena). A major goal was to find out whether and how co-design of software applications could improve citizen science based data collection, especially in terms of data quality and usability. An additional aspect was to learn how co-design processes may fit together with the program-oriented funding strategy of the German Helmholtz Association, which also includes remote sensing research and environmental science. The Nachtlichter project was coordinated by the GFZ German Research Centre for Geosciences; our sister project Fireballs collects data regarding fireballs (particularly large and bright meteors), and was coordinated by the German Aerospace Center DLR. This paper discusses only the Nachtlichter project. Further information about both projects is available from the project website (Nachtlicht-BüHNE, 2023).

2.1. Co-development process and timeline

The co-design process for Nachtlichter in some sense began before the project itself (Fig 3). In 2016, a group of 12 citizen scientists partnered with one of our authors (Christopher Kyba, GFZ) to develop a proposal for a citizen science project related to artificial sky brightness, for submission to the German Ministry of Education and Research (this proposal was not funded). When the Helmholtz Association issued a call for citizen science projects, Kyba reached out to this group, as well as to the other project co-leaders (Friederike Klan from DLR and Nona Schulte-Römer, then at the UFZ). Through a series of meetings between the project leaders and an expanded group of citizen scientists, the general idea for Nachtlicht-BüHNE and the two planned apps was formed. Because of the short timeline for the proposal writing, some decisions regarding the methodology were made in advance by the project coordinators, rather than open to co-design (for example that we would aim to count light sources within at least 3 contiguous areas covering at least 2 km^2 each). The main scientific aims of the project were also set. This ended up constraining the opportunity of the citizen scientists to select the research question and methodology, which we later learned was disappointing for some of the co-design team members, who would have preferred to be more involved already at this conceptual stage.

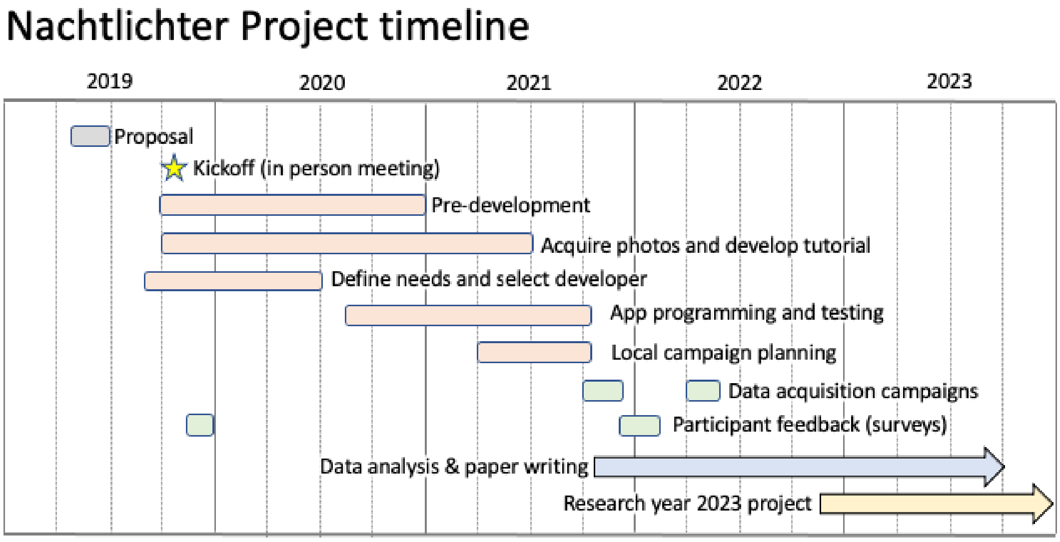

Fig. 3. Timeline of project activities.

Nachtlicht-BüHNE officially began on July 1, 2019. During the first months, we held a few online meetings to allow the group to start to get to know each other, and to begin planning the methodology. As a first action on the Nachtlichter side, we asked participants to go outside and walk some distance while tallying up light sources according their own individual classification scheme, and to return their results to the coordinators via email. We used these first results to develop a preliminary set of 13 categories of outdoor lights, and created a paper form that participants could use for future reporting.

The first major event of the project was a face-to-face workshop held on October 19, 2019 in Jena. This workshop brought together citizen scientists recruited by both teams, and both apps were discussed within two groups. Whereas the Nachtlichter citizen scientists generally had a strong prior connection to the theme of light pollution (for example due to prior activity as an amateur astronomer or environmentalist), the Fireball team included a broader cross-section of society, as people who had reported a recent fireball sighting to DLR by email were invited. The night before the meeting, some of the participants gathered to walk along a single street segment together, filling out their light tally on the paper form that had already been developed (see 2.2.). This exercise showed that there were considerable (up to approximately factor 2) differences in how many lights were identified by participants, indicating a need for training and standardization. By the end of the meeting, a general framework for the Nachtlichter method had been developed. Specifically, we decided that:

- participants would classify lights according to a selection of categories (to be determined)
- a single data point would generally consist of lights counted from one street corner to the next
- there was a need for an online tutorial to enhance the standardization and quality of data collection
- the app would have a “standard” and “expert” mode, and more detailed information such as the color of lights or their properties would only be collected in expert mode

This last idea was dropped during the process of developing the app and tutorial. Our team eventually decided that our training materials were sufficient that all participants should use the “expert mode”, and therefore the standard mode was never implemented.

2.2. Co-development of light source categories

One of the most essential tasks of the co-design process was to come up with a system for classifying outdoor lights. In developing the classes, we had two goals in mind. First, the classes should be as intuitive as possible, or at least easily understandable for project participants (after seeing photographic examples). Second, we wanted to have enough classes that different lighting types were well separated, but not so many that most participants would be unlikely to ever encounter an example of such a light (e.g. “flag pole lighting”). In the end, a set of 18 distinct classes were developed (including one “other” class for any lights that were otherwise unclassifiable).

To start this process, we first asked participants to go out onto the streets at night with a pen and paper, and make a tally of the different types and numbers of lights they counted while walking from one street corner to another. This first exercise provided us with both a set of light source types, including the nomenclature that participants chose to describe such lights on their own. It also gave us a first glimpse of how much time would be needed to classify one street segment. At our first workshop, we also discussed the problem of estimating the sizes of lit objects like signs and windows. Many participants were uncomfortable with the idea of estimating areas in square meters. We therefore made a decision to base our size classes on “human scales”, such as the approximate area covered by a person standing with their arms and legs spread (e.g. Fig. 4).

Based on these exercises and our discussions within the group, we developed a three page paper form with 18 categories of lights, divided into cells to allow additional information about the lights to be recorded (direction of emission, brightness, size, and color). We then asked participants to try to classify lights using this system. While participants had some difficulties because of the physical awkwardness of a 3 page format, in general we were happy as a group with the light source classifications we had chosen. Some refinements of the names and classes of the categories, as well as determinations of how to deal with category boundaries continued until the final prototyping of the app. The lighting categories are designed to be as all-inclusive as possible, so that even dim lights like lit doorbells are counted. The reason for this is that we did not want participants to have to make spur of the moment decisions about whether a light is “bright enough to be important”, or whether it was only there temporarily. The general principle is rather to obtain a snapshot of every single light that is present during the time that the observation is made.

We next asked participants to take photographs of the different light source types, in order to build a visual guide for developing our training materials. We aimed to have multiple examples for each possible direction (or size) for each of the 18 categories, and created a Google Sites page where these could be seen (some examples are shown in Fig. 5) as well as icons that make the categories more intuitive in the app. Based on this final set of light source types and classes, Yiğit Öner Altıntaş (a student working on the project) produced a set of drawings for use as icons in the app (Fig. 4).

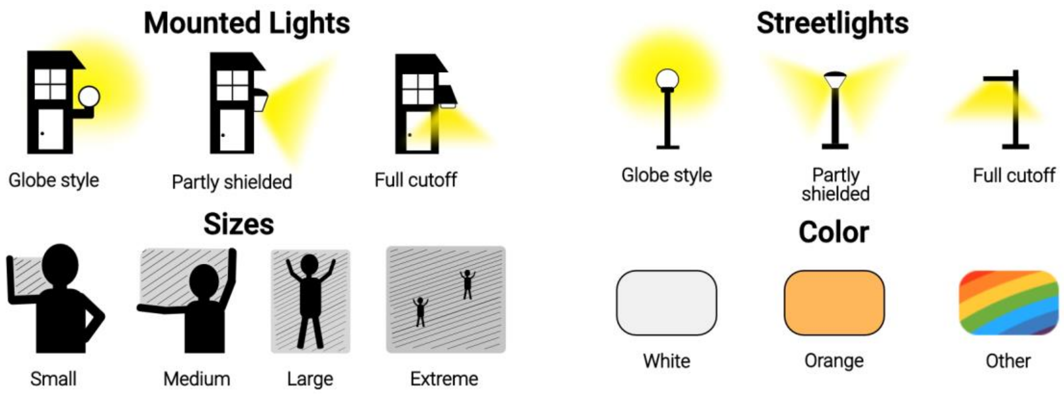

Fig. 4. Examples of icons used in the app. Design by Yiğit Öner Altıntaş.

In our opinion, the final set of light types does a reasonable job of describing the lights that are typical in Germany. A participant in the USA commented that they felt the app seemed better suited for Europe than North America, and that this was at least to some extent due to the choices of light categories. Ideas for streamlining the categories and use of the app in the future are presented in 6.4.

2.3. Co-development of the Nachtlichter app

Our original plan was to hold additional in-person workshops throughout the development of the app, but this was not possible due to the COVID-19 pandemic. In April 2020, we began searching for a developer to program the app. During this period, our team tested a number of existing citizen science data submission platforms to determine which might work for us. Nachtlichter differs from many citizen science experiments in which volunteers provide environmental data, in that our basic geographic element is a line, rather than a point, and this made some existing data collection applications inappropriate for the job. In the end, we selected the UK-based company Natural Apptitude, who provide support for a number of citizen science projects. The process of selecting a firm and writing a contract took considerably longer than expected, to some extent due to the COVID-19 pandemic, as well as due to a longer initial development time than expected. All of this meant that instead of holding our data acquisition campaign in the fall of 2020 as originally planned, it was held during the fall of 2021. In hindsight, the additional development time benefited the overall quality of our project.

With the developer selected, we began to develop a series of detailed flow charts showing how the app should function (Fig. A1). Natural Apptitude told us that the level of detail provided by our group both sped up the development process compared their usual experience with citizen science apps, and also reduced the amount of back and forth interaction. Before programming began, Natural Apptitude first sent our group a series of "wireframe" images, which showed what the actual screens would look like. Since these could be viewed on a phone, they simulated the user experience of an app, although with little functionality (clicking on most buttons did nothing, for example, and this unfortunately caused confusion for some members of our team). We used these wireframes to go onto the street and test how it would feel to actually use the app to count lights, and provided feedback to the developer based on these experiences. The first prototype was ready on July 19, 2021 and we began testing both the app itself, as well as the data exported from Natural Apptitude's database. This was less than two months until the start of our campaign (which could not be postponed in order to avoid cold nights and holiday lighting during November). As a result, testing was rushed compared to what we intended, and took place during the summer holidays, when some of our participants were not available. Nevertheless, Natural Apptitude delivered several updated versions of the app and improved it based on our feedback. Examples of changes made at this stage included the ordering in which the lights are shown within the app's "list view" (this was originally chronological), a decision of our group to introduce an "extreme" size category for illuminated signs, and a change in the name of one of the categories within the database.

2.4. Co-development of training resources, participant engagement, project logo and project website

Several parallel team activities continued while the process with Natural Apptitude played out. Throughout the course of the project, our citizen scientists went out onto the streets at night, and took hundreds of photographs of different types of light sources (Fig. 5). These photographs (see Kyba et al., 2023) helped our team to refine our light source categories into what was eventually 18 different types of sources (see 2.2). The second reason that we collected the images was in order to have visual examples for the training materials that we were developing (both for our online tutorial, and for a set of "light guides" available within the app).

Fig. 5. Examples of photographs of "lights mounted on buildings" collected by the citizen scientists. From left to right, these are fully shielded, partly shielded, and globe style.

This online tutorial was created by a team of students from Worcester Polytechnic Institute (WPI) as part of an internship program. The original plan was to have the students come to Germany and work with us at GFZ, but this was not possible due to the COVID-19 pandemic. (In fact, two groups of WPI students were affected – another team had tested of the paper form from the US, as well as research on the expectations of potential participants, one year earlier). The students therefore developed the tutorial remotely. The GFZ team met with the WPI group slightly more than weekly, but we also had two meetings between our full co-design team and the WPI group. Two of the WPI students spoke German, and this greatly facilitated the interaction, because several of the members of our co-design team are not comfortable speaking English. The tutorial was based on a framework developed by our co-design team (similar to that shown in Fig. A1), and is described in more detail in section *3.1*.

Another task which we undertook throughout the course of the project, and especially during 2021, was the recruitment of local organizers that could coordinate simultaneous data collection campaigns in different cities. This was central to the initial concept, as we aimed to observe lights over large areas without gaps, with boundaries corresponding to those of the 15 arcsecond pixels used by the Earth Observation Group (EOG) in their reprojected maps of lights observed from space (Elvidge et al., 2021). The minimum size therefore depends on latitude, and was about 0.15 km^2 in Germany, but larger campaigns, covering areas closer to 2 km^2 were initially planned. The campaigns are described in section *3.2*.

Last but not least, the co-design team helped develop and gave feedback on website texts about the project and a project logo that was created by a graphic designer. The development and release of the Nachtlicht-BüHNE project webpage took much longer than originally expected due to administrative processes regarding data privacy protection and website approval. The website became available only in mid 2021, which meant that our recruitment activities up until that time had taken place via other channels, such as email and Twitter. This was a source of frustration for several of the citizen scientists on our team, as they could not point potential participants to an official project website. We had originally hoped for the website to include discussion channels for participants, but we realized that we wouldn't have the time necessary to moderate the discussion (and an unmoderated discussion would create potential legal problems, because the hosting research institute would bear legal responsibility for all text that was posted). We therefore limited our interactions to online meetings and email (our sister project "Fireballs" also made use of Slack).

2.5. Co-development during the data collection phase

We declared the app officially complete on August 20, 2021, and the first official data was collected on the evening of August 23 (separately in two locations, by one of the dedicated members of our co-design team and one of the GFZ coordinators). Most of the data taking within individual cities began in September or October, after official kickoff events which included members of the individual communities and the GFZ team (see *3.1*). While we had originally planned to hold live events, all but two of these kickoff events had to be held online, due to restrictions imposed by COVID-19. Despite our testing phase (or perhaps due to its shorter than planned timescale), a number of participants had trouble getting the app to work in the first weeks. The most common problem experienced was due to a privacy issue, in that the browser did not have access to the phone's location. This necessitated the development of a "frequently asked questions" page in a shared Google document, which we released in both English and German. Using an online document had the benefit of allowing rapid translation by members of the core team in the cases that a new entry was prepared by someone who was not a native speaker in one of the two languages used.

As the local campaigns got underway (see 3.2.), the GFZ team was contacted by several individuals who wished to count lights in their neighborhood but did not wish to do so as part of a larger campaign. We therefore developed instructions specific to this case, and contracted the developer to add an additional functionality in the layers menu that would make it easier for participants to identify and count lights in areas that completely overlap EOG satellite pixels (see 3.2.2). We also added options to change the display of data (e.g. show "my transects only" or "show only unsurveyed transects") and to zoom to locations based on a name search. At the same time, we found that we were being contacted on occasion by participants who had made an error, and wished to have a survey removed from consideration. We therefore also had the developer introduce the possibility for participants to mark their own surveys as incorrect. These surveys are still saved in the database, but have a flag indicating that they should not be analyzed.

Our original plan was for the campaigns to be complete by the end of October, but it turned out that for various reasons this did not provide sufficient time for a few of the campaigns to complete the predefined transects. We therefore extended the official period of data taking to 14 November 2021. By the end of that period, transects had been assigned for 229 Earth Observation Group (EOG) pixels, and participants had completed all the necessary observations in 181 of them, covering a total area of approximately 22 km^2. Of the remaining EOG pixels, counting was never started in 23 of them, counting was not completed in 20, and 5 were deemed not appropriate for use in our analysis (e.g. including only a single street in the corner of the pixel). The typical DNB pixel radiances for these areas ranged from under 1 nW/cm^{2}sr to almost 100 nW/cm^{2}sr (Fig. 6). The median radiance was about 16 nW/cm^{2}sr and the mean was 21 nW/cm^{2}sr.

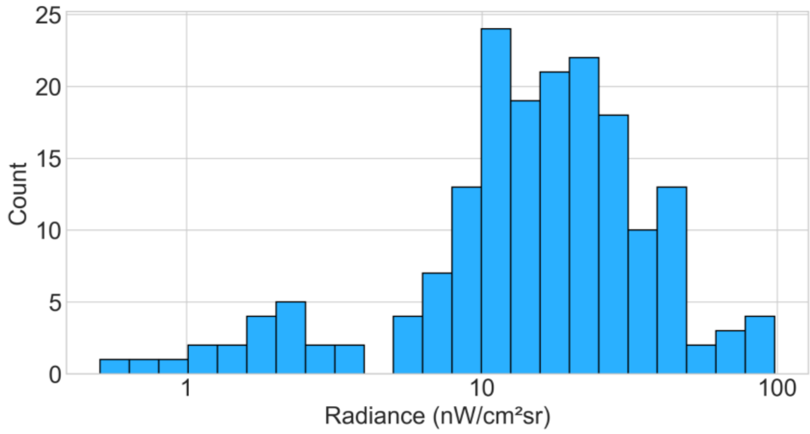

Fig. 6. Histogram of median radiance of EOG pixels surveyed by the Nachtlichter campaign. Radiance values are the median of the values observed in the composite images for September 2019 and 2020, and October and November of 2019-2021.

2.6. Co-development during the data analysis phase

With the data taking completed, the focus of the core team shifted to analysis. A subset of participants joined an analysis group that met weekly, while we continued to hold meetings of the full group every two weeks. The analysis group began their work by investigating the data quality and defining a final analysis dataset (see sections 5 and 6). When comparing transects surveyed at different times of night, we found that the numbers of some types of light sources (e.g. illuminated signs) change during the course of the night. We therefore decided to run a second "time of night" campaign during March and April of 2022, in order to generate an independent dataset for potential use in developing correction factors for the time at which each survey was taken. In parallel, the group at GFZ and the citizen scientists on the analysis team pursued additional analyses, such as examining how Nachtlichter data compared to city inventories (see 6.1), or examining the relationship between land use and type of light or density of light sources. These results have now been presented by both the project coordinators and individual citizen scientists at numerous conferences and workshops.

Throughout the analysis and paper writing period, the core citizen science team was informed and involved in the process. For example, a detailed outline of this paper was developed collaboratively with the full team in a (German language) online document before writing in English began. The team reviewed English drafts, and the contents of the document and the results of the analysis were discussed in German at our alternating weekly analysis group and full group meetings. The engagement of the citizen scientists and the co-development and improvement of the app has continued until today, as the project has moved into an unexpected additional phase in 2023 after another successful funding proposal.

3. The Nachtlichter campaigns

The development of a diverse set of information and training materials was critical to the success of the project, and considerable time was devoted to their preparation. In this section we first explain the steps we took to ensure comparable data was collected in widely separated cities (3.1.), and then describe the campaigns that took place in 2021 and 2022, including how we motivated participants to take part (3.2). All of the print materials and the tutorial referenced here can be downloaded from a repository hosted by GFZ data services (Kyba et al., 2023).

3.1. Standardizing data collection and sampling methods

The collection of a large amount of robust data was key to the success of the Nachtlichter project. The first challenge was thereby to not only mobilize participants to count lights after dark, but also to train them in using the app according to a standardized protocol, without hampering their motivation for the project (3.1.1).

3.1.1 Training Nachtlichter app users

While the participants were introduced to the broad strokes of the project and the use of the app through an information flyer, the project website, and kick-off events (see 3.2 for more detail), they still needed to undergo individualized training in order to ensure standardized data collection. We accomplished this through a mandatory online tutorial which showed participants how to classify lights while using the Nachtlichter app (e.g. with regard to the size classification of windows and signs). It also explained the categories that we had developed to distinguish different light source types (see 2.2), which are not common knowledge (e.g. we found that the terms “bollards” and “canopy lights” are unfamiliar to many people). When completing the tutorial, the participants receive a “completion word”, which is necessary to complete their app registration and be able to use all app functionality.

The student team that developed the tutorial based it on recommendations and feedback from our core design team. The students created the tutorial in English, and when it was completed we produced a translated German version (Kyba et al., 2023). The tutorial begins by explaining a few concepts that apply to all of the light sources, such as the difference between fully shielded, partly shielded, and unshielded lights. It then proceeds in steps through each of the different 18 categories of lights. Short quizzes are interspersed throughout to hold the participants attention and to make the experience more interactive and engaging. At the end of the tutorial, some general principles are presented such as how to create an account or new transect. The interactive presentation was developed with licensed software, which has caused some inconvenience in hindsight, as the citizen team members cannot adjust or create new versions of the tutorial (e.g. in Italian) without the license key and training in how to use the program.

Another way in which some of the local campaign organizers sought to ensure standardized data collection (see 3.2) was to hold in-person meetings, and either count lights together as a team, or to walk down a street and discuss the lights along it without submitting any data. This was particularly helpful for some new participants, who had concerns about what to do in cases when the light source didn’t match one of our categories. The teams in Dresden and Fulda in particular organized regular meetups for motivational reasons, during which participants met and then spread out in teams to efficiently complete the transects around their meeting point. Finally, newcomers were sometimes also paired with more experienced citizen scientists, to help them develop their confidence while undertaking observations together. Finally, in our online tutorial and in person meetings, we instructed citizen scientists to count lights with a partner. This was both to promote improved decision making, and also to ensure the safety of participants.

3.1.2 Selecting observation areas

In our initial project conception, we intended to define observation areas that were large (~2 km^2) compared to the true (~0.5 km^2) size of an individual DNB pixel. However, during the project development, the GFZ team was also working on a project involving DNB daily data (Kyba et al., 2021). They realized that for purposes of comparing surface lights to satellite data, it is advisable to survey areas in which the lighting practice in the survey area is similar to that outside of it. The reason for this is that the radiance in a single real DNB pixel depends to a small extent on the pixels around it; this is even more the case for the reprojected pixels that make up the Earth Observation Group (EOG) composites. Consider for example the two regions Fig. 7. In the region on the left, we can assume that the lighting character is very similar inside and outside the red box, as we see a rather homogenous residential area. In contrast, in the region shown at right, the lighting varies dramatically (from residential to unlit areas and industrial and parking lot lighting). This means that the radiance observed is not necessarily representative of the light sources that would be counted in the red area. Rather than defining single large areas in each city, we therefore decided to define multiple smaller areas of broadly consistent building structure and character (e.g. residential or city center areas). In practice, our regions are not always as consistent as the ideal case in the left panel of Fig. 7, but to the greatest extent possible we tried to avoid selecting regions similar to that shown on the right, especially in the large campaign areas for which we pre-defined in the app, in which streets and public spaces lights should be counted. The largest single pre-defined continuous area was in the town of Erlangen (1.8 km^2), the largest total area covered in a single city was in Potsdam (2.8 km^2), and the brightest of our large areas was in Dresden Altstadt (0.7 km^2 and DNB radiance ~75 nW/cm^{2}sr).

Fig. 7. Aerial imagery for two locations is shown with projected EOG pixels. The central (red) rectangle shows a reprojected DNB pixel, while the outer (yellow) rectangle shows the approximate size of a real DNB pixel. Note that in real operation, pixels will generally be tilted relative to North, and do not cover the same land area with each overpass (see e.g. Fig. 3 in Kyba et al., 2021). The figure is produced from screenshots of the Radiance Light Trends app (Stare & Kyba, 2019), and the background imagery is based on Bing Maps.

The next two sections describe how the first campaign was conducted in larger urban campaign areas (*3.2.1*), and smaller urban and rural regions (*3.2.2*), during 31 August to 14 November 2021. The third section (*3.2.3*) describes our follow-up campaigns in spring and fall of 2022, to study how lights change over the course of the night.

3.2. Data collection campaigns

Originally, only one data collection campaign was planned, to be held in the fall of 2021. After we began analyzing the data, we realized that we would like to have additional data regarding how lights change over the course of the night, and therefore organized a second, smaller campaign in spring of 2022. The first, main campaign took place in dozens of cities, mainly in Germany but with some international participation (Table 2). From the proposal stage, we had already planned large campaigns in Potsdam and Fulda, and as the project developed we recruited additional local coordinators (recruitment documents are included in the online supplement, Kyba et al., 2023). This recruitment continued into the period of the actual *multi-member* campaigns (3.2.1), and was then expanded to include campaigns by *individuals* (3.2.2) at smaller spatial scales than originally foreseen by the project (Tables 2 and 3).

Table 2. The time at which each city joined the project, and whether it was intended as a multi-person campaign in which new participants were recruited, or whether the effort was planned to be done by a single individual and their direct contacts. Campaigns which were planned but not completed are not shown. Note that three individual campaigns in widely separated parts of Berlin were undertaken by three different individuals. All locations are in Germany unless otherwise indicated.

Type	**Proposal stage**	**During app development**	**During campaigns**
Multi-member team	Fulda, Potsdam	Bochum, Bozen, Dresden, Erlangen, Preußisch Oldendorf, Würzburg	Cologne, Leipzig, Lutherstadt Wittenberg, Newport (Ireland), Split (Croatia), Trier
Individual effort	—	Achterwehr, Augsburg, Erfurt, Herzogenaurach	Berlin (3 areas), Borkheide, Caen (France), Freising, Gijzelbrechtegem (Belgium), Kutahya (Turkey), Leverkusen, Melsdorf, Rosenheim, Schönberg, Schönwohld, Tucson (USA), Westport (Ireland), Wetaskiwin (Canada), Zorge

Table 3. The size of each city area sampled, in terms of the number of covered DNB pixels completed during the fall 2021 campaign. Because the reprojected satellite pixel size depends on latitude, the area column is only approximate, and is oriented towards German latitudes.

Number of EOG pixels	**Approximate area**	**Cities**
1	0.15 km^2	Caen, Kutahya, Melsdorf, Schönwohld, Westport, Wetaskiwin, Zorge
2-5	0.3-0.75 km^2	Achterwehr, Augsburg, Bochum, Borkheide, Bozen, Freising, Gijzelbrechtegem, Leverkusen, Leipzig, Newport, Rosenheim, Schönberg, Split, Trier, Tucson, Wittenberg
6-10	0.8-1.3 km^2	Erfurt, Preußisch Oldendorf, Würzburg
>10	>1.3 km^2	Berlin, Cologne, Dresden, Erlangen, Fulda, Herzogenaurach, Potsdam

3.2.1 Large area, multi-member team campaigns

Our original aim when planning Nachtlichter was to hold organized campaigns in at least three cities, but from the start we hoped to have broader participation. In the early phases of the project, our focus was on developing the app itself, and as time passed we began to develop related materials which would eventually support the large campaigns (e.g. informational flyers, safety vests, and network building). One critical example was an information sheet and checklist that we developed for people or groups who were potentially interested in coordinating a large multi-member campaign. The information sheet included a checklist of activities they would need to undertake, as well as how we would support them in this, along with estimates of how much time would be required and how many volunteers they would need to motivate (recruitment documents are included in the (Kyba et al., 2023) supplement). Once potential organizers had expressed interest in organizing a campaign in their city, the GFZ team set up individual online meetings with them in order to answer their questions and make a time plan. From there, we met with most of these local organizers via videoconference every two weeks, throughout the summer and until the official kickoff of the local campaigns.

During our first meeting with prospective organizers, the GFZ team generally discussed the logistics of holding such a campaign, and what was expected of them. At a subsequent meeting, we examined the city layout and the satellite map (using Radiance Light Trends), and agreed upon a target area (or areas). We would then prepare preliminary transects for these areas (using data from either the Authoritative Topographic-Cartographic Information System ATKIS or Open Street Maps), and meet again to discuss these with the local team (Fig. 8). This was a critical step, because local knowledge was often necessary to know whether these places were really accessible to the public (e.g. walkways and alleyways marked on Open Street Maps), and also to lay out the positioning of the transect in a way that would make clear to the participants which areas and lights belong to which transects. The local teams also helped us ensure data protection and privacy standards (see 4.2), according to which we only counted lights on transects that included either no or at least four households. In some cases, participants later discovered that additional areas were accessible, and in this case added their own transects.

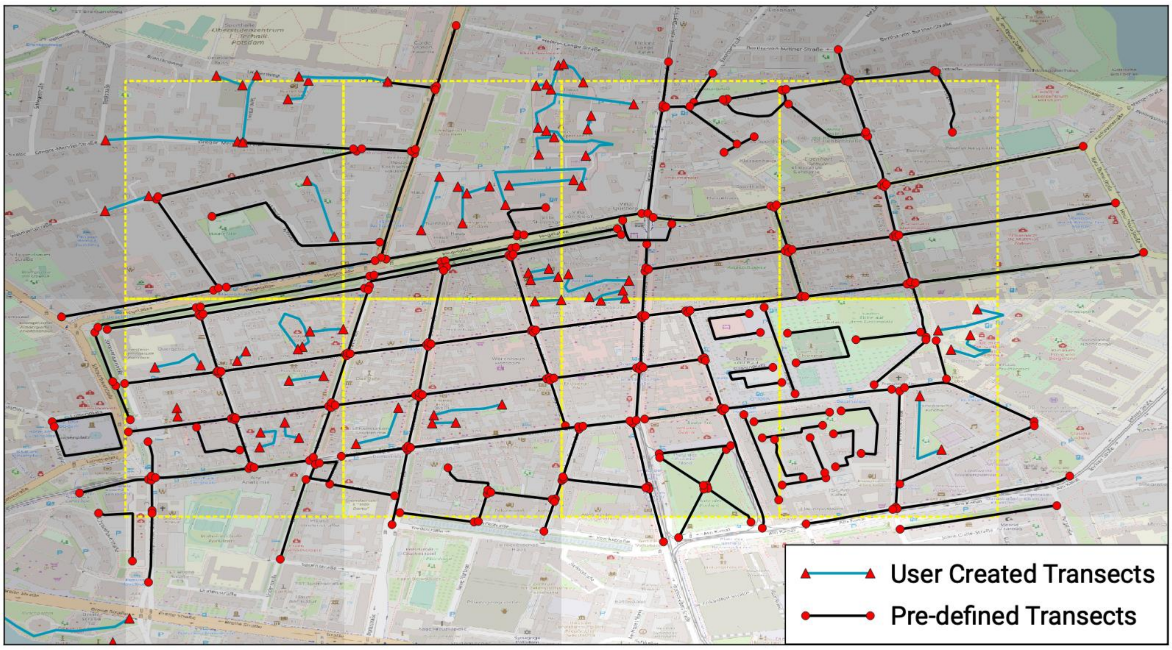

Fig. 8. Map showing the Potsdam Innenstadt (city center) and the transects surveyed in the project. Transects are shown as lines connecting red markers. Transects pre-defined by the organizers are shown in black, transects created by participants are shown in blue. Yellow dashed lines show the boundaries of EOG pixels. The large area with many user defined transects at top center is a restricted area, for which we received special permission from the city to survey on a single night. Map data copyright OpenStreetMap contributors and available from https://www.openstreetmap.org.

The following meetings with local organizers were devoted to ensuring that the campaign was proceeding as planned. We required local organizers to take a number of specific actions: they needed to establish a means of communication with the participants (most frequently via a mailing list, but sometimes using other media such as a WhatsApp group), plan a starting date for a kickoff event, and liase with local groups both to promote the event within established networks (e.g. from an observatory, environmental, or student group). We also instructed them to inform their city officials (including local police) about what was taking place, as well as why and when. In several cases, this led to individual cities promoting the event, for example via a citywide event calendar. The local organizers also found venues for the kickoff event, and established connections to local print, radio, and TV media. The GFZ team supported the local organizers in producing and distributing city-specific campaign flyers and press releases.

Mailing lists presented an unexpected difficulty regarding German publishing law. The local organizers were speaking with their own voice; they were not representatives of the GFZ and had no formal relationship with the research centre. For this reason, they needed to have their own "Impressum" (a legal statement of the authorship of a document which is required by German law). While the organizers had no objections to speaking in their own voice, a published Impressum requires publishing a mailing address. This was a problem for many of our organizers, as they did not wish to publish their home addresses online. In each of the cases, the GFZ team worked with the local organizers to find a solution, such as having a local organization be the official Impressum holder (e.g. the University of Würzburg). We feel it is important to highlight this difficulty, as it is likely to continue to be a problem for future decentralized citizen science actions, especially in the German context.

The overall data taking phase officially started on 22 August 2021, when the GFZ sent out a press release (GFZ, 2021). In most cities, however, counting did not begin until the official kickoff events. Nine official kickoff events were held. The first of these took place for the Erlangen campaign on 26 August, and the final was for the city of Cologne on October 8. Due to COVID-19 restrictions, we eventually decided in most cases to hold the kickoff events online (previous venue reservations were canceled). Only the Potsdam kickoff at GFZ happened face-to-face in a large lecture hall, and the Bozen kickoff was organized as a hybrid event.

The kickoff events lasted 60-90 minutes. The GFZ team explained first the science case for the project, second, details of how to take part (e.g. account creation), and third, general advice related to the method. We then invited the local organizers to present the area they had selected with us, and to discuss which of the predefined transects might present complications while counting lights (e.g. near town squares or at complicated intersections). One aspect of the project that the GFZ team stressed in these presentations was that the participants should try to do their best when counting lights, but also trust in their justment in cases where light sources do not fit neatly into a particular category. In these cases we encouraged the participants to simply make a decision, as quitting a survey or not including a particular light would both be worse for the project than a single mis-classification (see section 4.3 for a discussion of data quality). The kickoff audiences were in general very engaged, and typically asked follow-up questions for 20-40 minutes following our presentation. Since not all participants could attend these kickoff events, we also produced "how to take part" videos in both English and German.

The local campaigns differed greatly in how they proceeded (Zschorn & Mattern, 2022; Schulte-Römer et al., 2023). For example, the team in Bolzano (Bozen), Italy completed their entire region within two days of the kickoff event, and the GFZ team therefore worked with the local team to expand the area. The team in Potsdam worked rather continuously and independently throughout the entire campaign period, whereas the team from Dresden organized weekly counting events at which multiple people would meet at a single location and then fan out in groups (Zschorn & Mattern, 2022).

The first Nachtlichter campaign ended on 14 November 2021. Nearly all of the campaigns completed their goal of surveying every predefined transect (a few transects were removed when it was reported by a participant that the area was not actually public). There were three exceptions to this. First, there were a few locations (particularly internationally) where we met with organizers to define transects, but then a full campaign never developed, and no lights were counted at all. Second, in the city of Würzburg, our main campaign promotion was tied to a large public event. It seems that despite the call to participate reaching thousands of people, this public request was not as effective as more personal and individual recruitment through existing networks. In the end, 5 of the 7 EOG pixels in Würzburg were completed. Finally, in the city of Bochum, recruitment was done nearly entirely through selected school teachers, and due to school holidays and other issues (including COVID-19) the recruitment took place much later than originally hoped for. Of the 30 EOG pixels with transects defined in Bochum, 4 were fully completed, 4 were nearly completed, and 17 were never started.

During the campaigns, it became clear that campaign organizers were facing similar challenges, and could benefit from exchanging their best practices and solutions. We therefore organized an online mid-term event on 4 October 2021, in order to allow all the participants from different campaign areas to meet each other. This mid-term event also allowed individual participants who counted lights in areas with no multi-member campaigns to share experiences with other citizen scientists.

3.2.2 Smaller scale, individually run campaigns

As the main Nachtlichter campaign began and the press reported about the project, a number of people who did not live in one of the cities with multi-member campaigns contacted us as they were interested in taking part, but were also not interested in running a large campaign themselves (Table 3). We therefore developed a separate information sheet that explained how to run a self-directed "mini-campaign". A challenge of these individual campaigns was that since the participants would be defining the transects themselves through the app, we needed a way to ensure that they would select an appropriate EOG pixel (see *3.2*). We also needed a way for them to know where the boundaries of this pixel were. The "mini-campaign" information sheet used examples similar to those shown in Fig. 7 to explain what types of areas we were looking for. We encouraged people who were planning to do this to contact us, and the GFZ team set up Zoom calls with many of these participants to help them in their planning.

To address the issue of matching the streets to an EOG pixel, we initially asked participants to use the Radiance Light Trends app to see roughly where the pixel boundaries were, and plan on the basis of that. We found this to be too demanding, because it involved work prior to going outdoors and the need to remember a relatively large number of boundaries. We therefore contracted the developer to incorporate a grid layer into the app itself (see 2.1). This simplified the issue, as the participant could always see on the map where they were relative to pixel boundaries. As in the main campaign, we asked the participants not to end exactly at the pixel boundary, but rather to sample lights until an obvious break point (usually an intersection). This was done to ensure repeatability in the case of future campaigns.

In order to further help participants who chose this method, the GFZ team recorded an instructional video that mirrored the information we presented in our kickoff campaigns. As of September 2022, the German version of this video had been viewed 315 times, and the English version 145 times. In the end, the most active project participant (in terms of number of transects and lights counted) took part primarily by defining his own transects. The development of this method also made it straightforward for people who were traveling away from home to survey the places they were visiting, and this was done by several participants (including the most active participant).

As the campaign developed, we observed transects appearing on the map in places where we had no prior contact with a participant. In a number of these cases, we observed that there were some issues with the transect placement that would prevent us from using the data in our main analysis. Most typically, this was due to some streets being left out, or streets not being sampled all the way to the pixel boundary. The GFZ team therefore began contacting participants when we noticed that they were covering a large area. In most cases, we arranged a Zoom call with the participants, and were able to help them to complete their areas. In a few cases, we set up pre-defined transects for them, in order to assist with their data collection. This interaction led to some people joining our bi-weekly organization meetings, including the youngest known project participant, who is a school student and among the most prolific of data collectors.

3.2.3 Time of night campaign

After the main campaign was completed in November 2021, our group began analyzing the data. We quickly found that the time of night at which our observations were made played an important role for some categories of lights (particularly private windows, but in some areas commercial shop windows and illuminated signs that are switched off later in the evening). We therefore decided that it would be helpful if we were to intentionally collect an independent dataset to study how lights vary with the time of night, in order to calibrate the results of already collected app data. Producing this additional data in order to calibrate first results was particularly relevant for two reasons: First, the scientific aim of the project was to compare and to ground-truth satellite data on light emissions with our Nachtlicht data from the ground. However, the satellite passes over Germany well after midnight, whereas most of our data was collected before midnight. Second, the time of night campaigns could also show where commercial lights were switched off after shop opening hours. This information has a political relevance, as it reveals potential for reducing light emissions (which was a key motivation for several of our project participants.)

The requirements for this data acquisition were different from the initial campaign. For example, for the purposes of measuring how lights change, it is not necessary to completely survey large areas. Furthermore, in order to collect data about different light types, it was more important to collect data in non-residential or mixed-use areas (e.g. strictly residential areas tend not to have illuminated signs). We therefore adapted our existing print materials for individual campaigns (*3.2.2*) to this new task. We encouraged participants to make as many observations over as broad a time range as possible, and in particular requested that if possible at least one observation should be made before 20:45 and another observation made later than 23:15. The "time of night" campaign was conducted from 22 February until 13 April 2022. As with the main campaign, this meant that the campaign period overlapped the change between standard and daylight saving time.

The time of night campaign was also affected by geopolitical events. Following the Russian invasion of Ukraine on 24 February 2022, as Europe adapted to a new energy regime, some public and private actors took steps to reduce their energy consumption, including energy for outdoor lighting. During August 2022, the German government adopted a regulation designed to reduce energy consumption (EnSikuMaV - Verordnung Zur Sicherung Der Energieversorgung Über Kurzfristig Wirksame Maßnahmen, 2022). Among other things, this guideline requires most advertising signs to be turned off after 22:00. While we did not have resources to run a full campaign, we thought that it would be interesting to take Nachtlichter data during the fall of 2022, in order to examine how lighting regimes are changing. We therefore further adapted our instructions, and invited citizen scientists to make new time of night observations (the invitation made clear that we might not have the capacity to analyze the data). We chose to recommend completing one observation before 21:00, and starting a second observation after 22:30. The basis for these times was htat 22:00 is the switch off time stipulated in the new German law, and many businesses in Germany close at either 21:00 or 22:00. A total of 287 surveys were acquired during February to April 2022, and 237 surveys during September to November 2022.

4. Nachtlichter Data

4.1. Data structure

The raw Nachtlichter data consists of 3 separate comma separated values (CSV) files, which contain information about transects, surveys, and light source observations (Fig. 9). **Transects** are the geographical features on which Nachtlichter observations take place (Fig. 8), and are most typically a segment of a street running from one street corner to the next. **Surveys** are observation sessions that take place on a transect, and as such contain temporal data and a link to the transect. It is possible for a transect to have multiple surveys associated with it. Surveys also contain additional information about the conditions of the street itself at the time of the observation (for example, how many cars are present, and what fraction of lights were set off by motion detectors). **Light source** observations are the actual counts of individual light sources observed on a single survey. Surveys typically have a large number of light source observations, and the same overall type of source is often included in the file more than one time (e.g. with different shielding or size characteristics).

The format of the "nightlights-transect.csv" file is shown in Table 4, with an indication of data types and example values. The first line in the data file is a header, and the following lines contain the data itself. When transects are first entered into Natural Apptitude's COREO database system, each transect is assigned a unique ID by the COREO system. This ID is used by the COREO system to link surveys to a particular transect. Each transect also has another identifier, shown in the column "unique ID". For predefined transects, this is a number that we used when creating the transects. It consists of a country phone dialing code (in the example case 49 for Germany), followed by a 3 digit number which identifies the city (007 for Bochum), and a 5 digit number which counts up from 1 (00222 in this case). These numbers were useful for us internally during the development phase, and can be ignored for external analyses. In the case of user created transects, a large unique number is assigned by the COREO system. The "name" field frequently contains street names obtained from Open Street Maps (these are not unique), and is mainly used for display. The user generated field indicates whether the transect was predefined by the campaign organizers ("false") or defined by a user ("true"). Finally, the username indicates the name of the user who created the transect ("admin" for predefined transects).

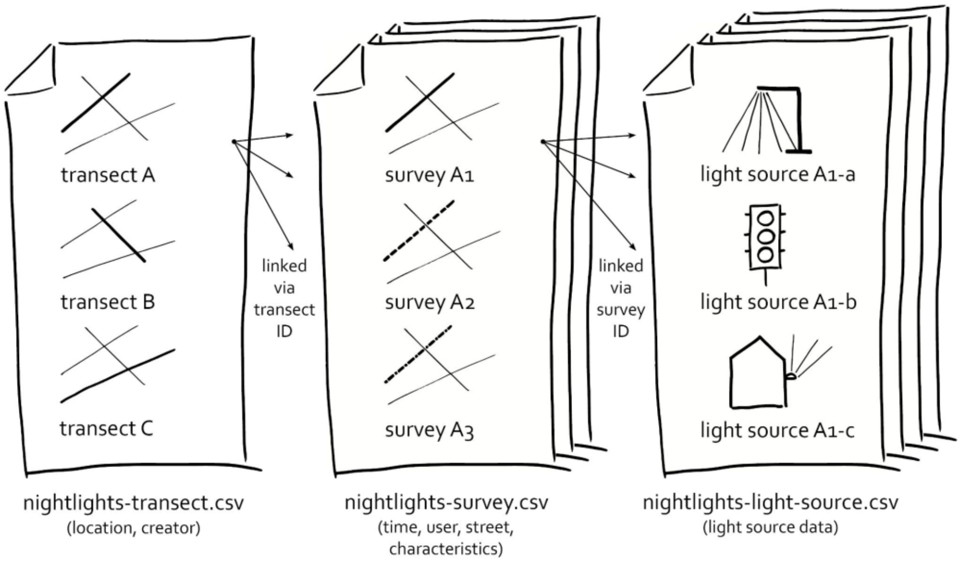

Fig. 9. Logical structure of the Nachtlichter data storage (graphic by Maria Zschorn).

Surveys are contained in the "nightlights-survey.csv" file (Table 5). As was the case for the transects, each survey is assigned a unique ID by the COREO system at the moment it is uploaded. Surveys are linked to the COREO transect IDs via the value in the "Transect ID" column. Multiple surveys may be performed on a single transect. The start and end times represent the moments at which the participant started the survey and sent it to the server, respectively. The creation date represents the moment at which it was successfully saved to the server (this could be significantly delayed in the case that offline participation becomes possible in the future). The "status flag" can have values of "flagged" (indicating the record should not be analyzed), or "public" (indicating it is a valid record). There are also three flags association with each survey regarding the height of street lights relative to obstacles ("shorter" or "taller"), the frequency of vehicle traffic ("very few", "one per minute", "several per minute", or "nearly continuous"), and the relative number of lights turned on by motion sensors ("none", "some", or "many"). The repetition of the flags in the data file is related to the COREO database, either value can be checked.

An unidentified error caused some number of surveys to be added to the database multiple times. These surveys have different IDs, but identical start and end times. Newly acquired raw data must therefore be checked to remove such duplicates (see 5). In a small number of cases, participants broke an observation of a single transect into two surveys. Participants have told us that in some cases they noticed one or more additional lights after completing the record, and therefore created a second record. Such surveys can be identified by a large difference in the number of lights between the first and second survey, and a short time between the surveys (generally less than 10 minutes). In a very small number of cases, participants divided the street sides between two people, and submitted independent surveys. Such records can be identified by two surveys with very similar (but not identical) starting and ending times, and very different records in the lights counted. Finally, these errors need to be distinguished from the rare cases where participants made independent surveys at the same time. Such surveys contain valid data, and can be identified by having similar start and ending times, and also similar numbers of light sources observed. Upon publication of our analysis results, we will provide a cleaned version of the data.

The main data collected during an observation is saved in the "nightlights-light-source.csv" file (Table 6). The data are broken up according to the different classes of lights observed. Since there are 18 light types, 4 size classes, 3 color classes, 3 direction classes, and 3 brightness classes, there may be dozens of light source lines associated with a single survey. Light source data from a single survey are not always listed consecutively in the file, which means it is essential to group the light source data according to survey ID before analyzing the data. Each permutation of light sources observed is recorded on a separate line, and the sum of lights of that type along the transect is reported in the “count” field. Similar to the survey file, some variables (e.g. “color” and “color value”) are stored identically twice, and either may be used.

In general, an analysis of the Nachtlichter data should start by selecting a geographic area and finding the associated (valid) surveys in the area. The light counts for these surveys can then be summed. Examining sums of lights directly from the light source data file is not recommended, as some lights will be counted multiple times (in cases when more than one survey was completed for the same transect), and the analysis recommendation status of each survey (public or flagged) does not necessarily propagate to the light source file.

4.2. Protection of personal data

During the development of the Nachtlichter app, we were confronted with the question of whether the fact that a light is on represents “personal data” (*personenbezogene Daten*) in the sense of European and German privacy laws. On the one hand, if you know who lives in a certain house and track at what time their lights turn on and off, you could infer their comings and goings, as well as the times that they are awake. A project that involves taking time series photos therefore ought to take care in this regard (see e.g. Dobler et al., 2015). In our project however, we have no detailed time series, and the fact that a light is on is not a definitive indicator of presence, as the light could potentially be on a timer. Discussions of this point with lawyers and the citizen science community revealed a diversity of opinions, indicating that this is a legal gray area.

We eventually developed a few rules to ensure the protection of privacy for people living along the street segments we sampled. First, we decided from an early stage not to include photographs as part of the data acquisition. Second, we decided that a transect must always contain either zero households (e.g. in an industrial or commercial area) or at least four households. In this way, in almost all cases it should be difficult or impossible to infer presence and/or activity on the basis of our data for a specific home. This complicated the transect layout in a few areas, particularly for unusual configurations of street intersections with short distances between corners, as well as in some rural areas where homes are separated by relatively large distances. Our usual approach in these cases was to lengthen one or more of the transects, sometimes using a U or L shape which extended past multiple street corners rather than just between two.

In addition to the privacy of the people living along our survey areas, we also took steps to ensure the privacy of the project participants. The personal information we collected was limited to the participant’s name, email address, a username, and the times and places at which they made observations. Names and email addresses were stored on a server inside of the EU, and are only accessible to the project coordinator and database manager. An email address was necessary in order to confirm the registration, and to allow participants to recover their account in the case they forgot their password. During the registration process, we allowed users to opt out completely of receiving email (even with regard to questions about their data).

We decided to make the usernames part of the public data record for several reasons. First, this allows the participant to receive credit for their contribution. Second, it allows someone analyzing the data to evaluate the experience level of the participant (e.g. based on the number of surveys completed by the user). Third, it allows people using the data to recognize if a street was surveyed by the same person multiple times, or different people (e.g. for evaluating systematic differences between participants). We reminded participants that their username would be connected to locations at which they observe and made public, and for this reason strongly recommended that users select a pseudonym that is not clearly related to their real name.

Finally, participants had the option to attach a text comment to their observation. This feature was requested by some participants who wished to make notes for themselves. Because we did not want to have to approve observations before they are shown online (e.g. to avoid profanity or links from spammers), we decided to make these comments visible only to the participant who made them. This functionality was accidentally forgotten during the programming phase, and was turned on in a new version of the app in 2023.

Table 4. Format of the transect data file, data types, and an example line. The first line is the header from the file. * The linestring is too large to fit in the table format. Here is the value for this example transect which consists of only a start and end point: "LINESTRING(7.21463421267283 51.4715983752425,7.21483743549771 51.4710469061731)"

ID	Creation date	Geometry	Status flag	Unique ID	Name	User generated	Completion status	Username
integer	date & time	Linestring (lat lon pairs in epsg:4326 WGS84)	public/private	integer	string	boolean	boolean	string
14814983	2021-08-20 15:04:17.895+00	see table caption*	public	4900700222	Hubertusstraße	FALSE	FALSE	admin

Table 5. Format of the survey data file, data types, and an example line. The first line is an edited version of the header from the file. "SL RH" stands for "Street lights relative height", "VF" stands for vehicle frequency, and "MS" stands for "motion sensor activity".

ID	Created at	Status	Start time	End time	SL RH	SL RH value	VF	VF value	MS	MS value	Transect ID	User name
integer	date & time	string	date & time	date & time	string	string	string	string	string	string	integer	string
14831290	2021-08-23 18:28:24.953+00	public	2021-08-23T18:16:08.140Z	2021-08-23T18:27:54.615Z	shorter	Shorter	nearly_ continuous	Nearly continuous	none	None	14831291	ewei

Table 6. Format of the light source data file, data types, and an example line. The first line is an edited version of the header from the file. “Col” stands for “Color”, “Bri” stands for “Brightness”, “Var” stands for “Variant”. There are three possible values for color (Orange, White, or Other), three possible values for brightness (Dim, Normal, Bright), and seven possible values for variant (Small, Medium, Large, Extreme, No Shield, Partly Shielded, Fully Shielded).

ID	Created at	Status	Type	Type value	Count	Col	Col value	Bri	Bri value	Var	Var value	Survey ID	User name
integer	date & time	string	string	string	integer	string	string	string	string	string	integer	integer	str
14831298	2021-08-23 18:28:25.038+00	public	video screens	Video screens	1	orange	Orange	normal	Normal	small	Small	14831290	ewei

5. Data cleaning and analysis and publication plans

After the main Nachtlichter campaign was completed, we formed a new group of participants who were interested in contributing to the analysis of the data, which met every two weeks. In addition to scientific analyses which are ongoing, this group was charged with evaluating the data quality and developing the final dataset. For our comparison to satellite data, it is necessary that each transect have a single set of observations. In cases where a transect had more than one survey (see Fig. 9), we intended to average the surveys together. Before this was done, we compared the number of lights observed between the two surveys, and discovered a small number of cases in which the number of lights counted differed dramatically.

We investigated the cause of these differences, in some cases contacting the participants when they had given us permission to do so. The most common were cases in which a participant had noticed one or more light sources after having submitted the survey. Since we did not program functionality to edit surveys, some participants decided to make a second survey which included only these lights. This led to a consistent and easily identifiable pattern in which two surveys were submitted at very short times from each other, with dramatically different numbers of lights. We therefore merged these surveys into a single survey when building the final dataset. A second cause was due to a software error, in which the same data was entered into the database twice. These records are easily detected, and we deleted or flagged the duplicate surveys. A more serious problem occurred in two cases in which a participant had not understood the task, and sampled the two sides of the street separately in two surveys. Based on feedback from the participant, these surveys were merged to create a single survey. In total, 20 surveys were merged. To put this in context, as of December 17, 2021 a total of 4,576 surveys had been recorded.

Finally, there were 16 cases in which we flagged a survey as being not suitable for analysis (this was done using administrator privileges in the database, so anyone doing future analyses need not take action as long as they reject flagged records). The surveys were flagged for a variety of reasons, but most frequently because the data did not appear to make sense relative to other Nachtlichter data or street view imagery. We believe this occurred in a few cases when a participant clicked on an incorrect transect when starting a survey (e.g. accidentally placing a survey on the last transect they had sampled).

Our main co-design team has continued to meet every two weeks since the main campaign was completed. They have played a role in developing this paper, for example by editing the outline and initial text, preparing figures for the paper, and developing criteria for co-authorship decisions. The group has also worked towards a new project that expands upon the original Nachtlichter app described here.

6. Methodological strengths and limitations

In this section, we reflect on the methodology that we have developed. We begin with an examination of the data quality, and then discuss the strengths of our approach (compared to other methods) and its inherent limitations.

6.1. Data quality

One basic question in evaluating data quality is “to what extent does the data correctly represent reality?” With an instrument such as a luxmeter, this can be quantified by testing the repeatability of observations taken under different lighting conditions and with different meters, in order to determine the systematic uncertainty of a single observation. Within Nachtlichter, there are two main potential sources of variability. First, different participants may approach the task with greater or lesser care, which could lead to different counts. For example, in the case of a cursory view of a building from only one direction, a participant may not notice a light source that is hidden behind a wall or object. It is also possible to become confused as to whether one has already classified a light source (especially with street lights, which often have an identical appearance along a transect). Second, Nachtlichter observations inherently involve subjective decisions about the number, sizes and type of light sources (e.g. app users had to decide which transect a light source should belong to in the case of one installed exactly on a street corner at an intersection). Moreover, not all light sources are easily classifiable within our system.

Different counting practices and subjective decisions likely lead to variability from one observation to the next, even for a single observer. We evaluate the data quality in two ways. First, we compare the results of different surveys on the same transect to each other, and second, we compare the number of streetlights recorded by Nachtlichter participants to databases of the positions of public streetlights.

6.1.1 Similarity of independent observations by multiple observers

During the main campaign, the team in Potsdam selected one transect in the city's pedestrian area as a test street in which they aimed to have observations from as many participants as possible. In total, six participants performed observations on this street over the course of the campaign (Table 7). The time of night plays a role in the total number of lights counted for many of the categories (see 3.2.3); the observations made before 22:00 are much more consistent than those observed later, for which many fewer signs and lit windows were recorded. The number of streetlights counted is much more consistent than the other categories, although the observer who took data at 20:26 apparently counted one set of streetlights twice (the streetlights on this street are arranged in pairs, so a single counting error is doubled). With the exception of the two surveys with a start time of 19:39, the observations were not made on the same nights.

Table 7. Summary of surveys on a single transect on Brandenburger Straße, Potsdam (Transect ID 14816564). Each column shows the total number of lights counted for each light type. For simplicity, the lights from each type have been summed regardless of their additional attributes (e.g. dim vs bright and size of signs). The mean and standard deviation (SD) are shown in the final column.

Start time	**19:39**	**19:39**	**20:26**	**21:12**	**22:16**	**1:23**	**Mean (SD)**
Streetlights	14	14	16	14	14	14	14.3 (0.8)
Private windows	23	16	11	20	8	7	14 (7)
Commercial windows	24	21	21	25	14	12	20 (5)
Lights on buildings	2	3	3	2	2	0	2 (1)
Doorbells	4	1	6	3	0	1	3 (2)
Canopy	6	0	0	10	0	0	3 (4)
Strings	0	0	8	0	0	0	1 (3)
Orientation	0	0	0	0	0	1	0.2 (0.4)
Signs	15	19	19	17	12	6	15 (5)
Total	88	74	84	91	50	41	71 (21)

Most observers did not report any light strings or canopy lighting, whereas some observers reported quite a few. This might seem surprising at first, but it is most likely due to the fact that individual lights are often grouped as part of a single installation (Fig. 10). If an observer misses one such light, they are likely to miss all of them. The light strings on the balcony in Fig. 10 are located on this transect, and the photograph was taken by the two observers that started their surveys at 19:39. After completing their surveys independently, the two participants walked the street together in order to compare their observations. It was during this comparison that they observed the light strings that they both had missed as part of their survey. Notwithstanding the double counting error on street lights, this suggests that the Nachtlichter sum of light sources is more likely to be an undercount than an overcount.

Fig. 10. Two street-level views of the same building. The illuminated light strings on the balcony cannot be seen by an observer standing in the middle of the street. They are only visible when standing very close to the wall of the building on the opposite side of the street.

The campaign organizers in Erlangen also arranged for one transect in the city center to be classified by multiple observers. In this case, 5 surveys were started at roughly the same time and date, while one survey was made on a later date and at a later time of night (Table 8). The group had considerably different levels of experience with the project. As was the case for Potsdam, the agreement was greatest among the participants for the sum of street and path lights, and there were considerable differences in the number of canopy lights reported. Total counts might also vary for signs, commercial and private windows as the counting units for those light types involve subjective judgements.

Taken together, these data suggest that the variability from observer to observer in the total number of lights counted along a transect at a given time is likely in the range of 10-20%, with smaller variability for some classes of lights (such as streetlights) and larger variability for others. This variability is not unexpected, given the subjective nature of parts of the task (e.g. judging the size of irregularly sized windows) and differences in the attention, motivation, and experience of different participants. For comparison, the standard deviation of DNB radiance observations from month to month for the individual EOG pixels containing these streets is 21% for the Potsdam location and 28% for Erlangen. In the same way that repeated observations reduce errors in radiometric observations, the variability of the average number of lights counted by multiple observers will be smaller than the variability from observer to observer.

Table 8. Summary of surveys on one transect in Erlangen (Transect ID 14815871). Each column shows the total number of lights counted for each light type. For simplicity, the lights from each type have been summed regardless of their additional attributes (e.g. dim vs bright and size of signs). The mean and standard deviation (SD) are shown in the final column.

Start time	**20:06**	**20:11**	**20:29**	**20:30**	**20:31**	**22:21**	**Mean (SD)**
Streetlight and path lights	26	22	25	25	24	22	24.0 (1.7)
Private windows	0	10	3	0	1	14	5 (6)
Commercial windows	28	13	19	20	19	13	19 (6)
Lights on buildings	0	0	3	0	0	0	0.5 (1.2)
Doorbells	2	0	0	0	0	0	0.3 (0.8)
Canopy	30	0	8	15	12	4	5 (3)
Strings	6	8	1	8	8	1	5 (3)
Signs	18	16	19	21	11	13	16 (4)
Total	110	69	78	89	75	67	81 (16)

6.1.2 Comparison of Nachtlichter street light counts to city lighting maps

Many cities have a digital record of the position and type of public lighting. For some of our larger campaign locations, we compared the number of lights in these databases to the number of street, path, and parking lot lights recorded by our observers. An example of such a check is shown for an area of Dresden in Fig. 11. Shaded regions have been drawn around each transect, in order to assign street lights to one street or another, and the number of counted street lights is labeled for each street. In all but one case, the sum of Nachtlichter streets is within one of the numbers recorded by the city. The street with the larger difference includes a schoolyard, and it may be the case that one of the Nachtlichter participants classified lights on the schoolyard as streetlights rather than path or parking lot lights. Some level of discrepancy is expected at this local level, due to occasional unclarity with regard to the case when a light is located right at the corner of two intersecting streets. In our training materials, we asked participants in these cases to ideally make observations on both streets, so that the light would be only counted once. However, it is likely that in some cases lights were excluded or double counted for this reason. The identical problem affects our geographical information system assignment of the number of lights on each street segment.

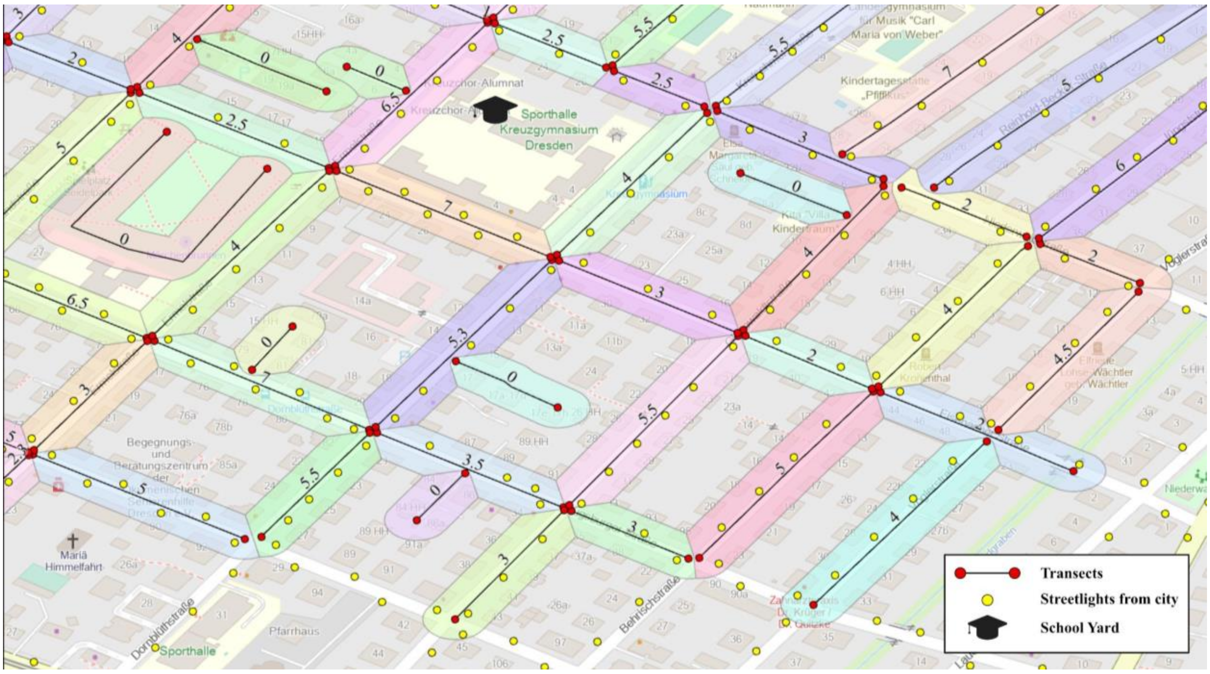

Fig. 11. Map of one of the Nachtlichter areas in Dresden, with lights managed by the city marked as yellow circles, and Nachtlichter transects shown as black lines. The transects are surrounded by a colored region of up to 20 meters from the transect, in order to indicate that participants count lights over a larger area than just the street. Each transect has the number of streetlights counted by Nachtlichter participants near its center. Fractional values can occur when more than one observer surveyed the same transect.

We compared the number of lights counted by Nachtlichter participants to the city streetlight count for each transect in five different cities (Table 9). In about one third of cases, the two numbers matched exactly, while in about two thirds of cases the numbers matched within one. Larger differences can arise for a number of reasons. First, public street lights are sometimes not illuminated. This most commonly occurs when a single streetlight is defective, although larger clusters can also occur (Chalfin et al., 2022). For example, in one case reported to us by a Nachtichter participant, the public lights were off along the length of an entire street segment, due to construction. Second, public databases only include the streetlights under municipal responsibility. Yet in many cases, privately managed functional lighting on private parking lots, footpaths and driveways are not distinguishable from streetlights. This was frequently the case for the commercial area examined in Leipzig, as well as the (largely commercial) Musikerviertel region examined in Fulda. As a result, Nachtlichter participants sometimes incorrectly classified parking lot and path lighting as street lighting. Third, in some cases, public databases also include light sources that are not typical street lights, and are likely to be classified and counted by Nachtlichter participants in a different app category (Fig.12). Fourth, in some cases the light sources in the city database corresponded to multiple luminaires, but were only counted here as a single luminaire (this was done because we didn’t want to edit the tables by hand, as it would make confirmation more difficult, and in any case we don’t expect an exactly precise count).

Table 9. Comparison between the number of streetlights categorized by Nachtlichter, and the number in the city street light maps within the buffer zone of the transect (see Fig. 12). The percentage values show how often for each city the Nachtlichter count matched that of the city's count to within the given difference level. Leipzig is shown once including all transects, and second including only the transects on which city operated streetlights are present. In addition to the 3 large areas, the numbers for Berlin include a small number of user-generated transects in other parts of the city. The numbers for Dresden represent only the 4 pre-selected areas.

Difference	**Berlin**	**Cologne**	**Dresden**	**Fulda**	**Leipzig (all)**	**Leipzig (city only)**
0	33%	36%	43%	30%	31%	17%
±1	61%	69%	66%	62%	53%	56%
±2	74%	83%	80%	79%	63%	69%
±3	84%	89%	85%	83%	72%	81%
±4	87%	91%	91%	86%	78%	89%
±5	92%	94%	93%	88%	81%	89%

Fig. 12. Three examples of lights operated by the city of Dresden that are in the city "streetlight" database, but are not likely to be classified as streetlights by Nachtlichter participants. The light on the left should be categorized as path lighting, the light at center as either path or parking lot lighting, the light at right as a light mounted on a building. (In the case of the light at the right, the label below the luminare clearly indicates that it is a publicly operated light.) All photos by Georg Sulzer.

Despite all of these potential sources of difference, the total number of streetlights counted by the Nachtlichter participants reasonably closely matches the number in the city lighting database when summed over the complete campaign areas (Table 10). When considering only street lights, the Nachtlichter total agreed very well (within 8%) with the official count in Berlin, Cologne, and Dresden. Larger differences were observed in in Fulda (+39%)

and Leipzig (+25%), but both of these include areas for which we know a large number of privately operated functional light sources are in service. When we compare the number of city reported streetlights to the sum of Nachtlichter street, path, and parking lot lights, the Nachtlichter project participant totals are considerably larger than those of the city in all cases: 38% larger for Berlin, 34% for Cologne, 17% for Dresden, 57% for Fulda, and 132% for Leizpig.

Table 10. Comparison of the total number of lights counted within the analysis area for the city street light database to the number of street and path lights classified by Nachtlichter participants. Fractional values are possible in Nachtlichter in cases when more than one survey was acquired, and the results were not identical.

	Berlin	**Cologne**	**Dresden**	**Fulda**	**Leipzig (all)**	**Leipzig (city only)**
Sum of lights in city database	1424	1173	2099	953	199	199
Sum of Nachtlichter streetlights	1488.0	1251.2	1977.5	1335.7	380	241
Nachtlichter street+path lights	1919.0	1565.7	2470.2	1511.7	464	314

Taken together with the results presented in 6.1.1, these results give us confidence that the sum of lights counted by Nachtlichter participants is an sufficiently accurate reflection of the true situation on the ground at the time at which the survey was completed.

6.2. Strengths

There are numerous ways to obtain information about the light environment in the context of built-up areas. For example, imagery data from above may be taken with uncrewed aerial vehicles (Bouroussis & Topalis, 2020; Li et al., 2020), aircraft (Kuechly et al., 2012; Hale et al., 2013; Ruhtz et al., 2015; Wuchterl & Reithofer, 2017), high altitude balloon (Bettanini et al., 2022), or satellite (Elvidge et al., 1997; Li et al., 2018; Sánchez de Miguel, Zamorano, et al., 2021). These methods have an advantage over Nachtlichter of being able to acquire data over a large area in a short time period, with relatively low human effort (at least in terms of being outside at night). However, these "view from above" methods all have the drawback that they do not acquire observations from the "person on the street perspective". They have reduced sensitivity to horizontal emitters (such as signs and shop windows), and are not able to observe some light sources at all (e.g. canopy lights). Their low resolution (compared to human vision from the ground) makes distinguishing numbers of lights and their types difficult or impossible.

As we were developing the app, participants often asked whether it would be possible to use camera systems (similar to Google's Street View) or irradiance measurements (Aube & Houle, 2022), instead of counting and classifying lights by hand. While such methods may be more convenient, they suffer from the drawback that not all light sources can be seen from the street, and that intelligence is needed to convert such measurements into useful counts of light sources (Fig. 13). While it is quite easy for a human being to recognize that the light on the image at right comes from a floodlight, an automated computer system is likely to have difficulties in correctly distinguishing reflections from directly emitted light, and especially interpreting the source of the light. The major strengths of the Nachtlichter app compared to other methods are therefore:

1) the application of human intelligence to determine classifications of different types of light emissions
2) the ability of the method to sample all the different light sources that occur in urban areas (as opposed to the limitation of only public lights in street lighting databases)

Fig. 13. Photos illustrating the advantage of having walking participants do lighting classifications, rather than automated acquisitions while driving. In some cases, lights which cannot be seen from the street (left) are visible from pathways (center). In many cases, the light which is seen is reflected, rather than directly emitted (right), and would be difficult for a computer to classify.

In addition to assembling a unique, comprehensive, and useful dataset, another outcome of the app is that participants are changed by taking part. A near-universal experience was that the use of the app sensitized participants to see their night-time environments with different eyes. This was reported in participant feedback during our many zoom meetings, joint light counting tours, and also from the final participant survey (n=97). This change of perception included the realization that there are far more, and far more diverse, light sources in their environment than they had ever appreciated, as well as increasing participants' awareness of unnecessary and badly installed light sources (e.g. upward shining lights, bright illuminations on empty streets, etc.) This critical awareness is reflected in one survey participant's final remark about the project: “I would like to see the results made available to key legislative and urban planning bodies and luminaire manufacturers.” This feedback is representative of many discussions we had during our team meetings about lighting practice, concrete improvements that could be made on local scales in our participants' communities, and political measures that should be taken to mitigate light pollution. Participation in the project gave many individuals a sense of responsibility for, and ownership over, the data, as well as a feeling of accomplishment at having completed the survey over a large area. Some of our participants are light pollution activists, and either have or intend to re-use the data for non-academic work (e.g. in discussions with politicians regarding lighting changes or proposed curfews). The co-design and intra-team dynamics, as well as the motivation of the participants are discussed in more detail in Schulte-Römer et al. (2023).

Finally, participants who are or were actively engaged in the co-development process reported that they enjoyed contributing to scientific evidence production, and have gained a better understanding of scientific practice. It is important to note, however, that this better understanding was not necessarily reflected in a greater trust in the process. In some cases, critical questions regarding our scientific practice were raised, frequently including the question of whether having people make (sometimes subjective) decisions about lights is an appropriate methodology. These uncertainties can be interpreted as another sign that participants have moved closer to the ‘core set’ of scientific evidence production and towards acting as critical specialists (Collins, 1988).

6.3. Limitations

Despite the overall success of the project, there are a number of limitations associated with a citizen science approach in comparison to the radiometric approaches discussed above. These can be divided into three classes: limitations related to the light sources, limitations related to our categories, and limitations related to using an app. These are discussed below, and followed by a short discussion about limitations associated with our particular project.

While it is an advantage that citizen scientists can move around in the street area and identify lights that are not visible from the street or above (Fig. 13), we are limited by the fact that our participants can only make observations from publicly accessible areas. This means that lights installed on the back sides of buildings, on their roofs, and in some cases on their grounds may not be counted (Fig. 14). In addition, there is a potential for confusion regarding whether an adjacent off-street area was counted in cases where the public right to access is unclear (for example, a restaurant's Biergarten, or the grounds or parking lot of a hotel). This could present a particular problem for follow-up observations. Next, many lights are not illuminated during the entire night (as discussed in *6.1.1*), or they may be illuminated only on certain days of the week. This means that Nachtlichter observations represent a single snapshot in time (this problem is shared with many of the radiometric methods).

Finally, a small fraction of lights are intermittent (e.g. dynamic architectural lighting, flashing safety lights, flicker from a window illuminated only by reflected light from a TV inside), and our app does not acquire information about whether the light is steady or intermittent.

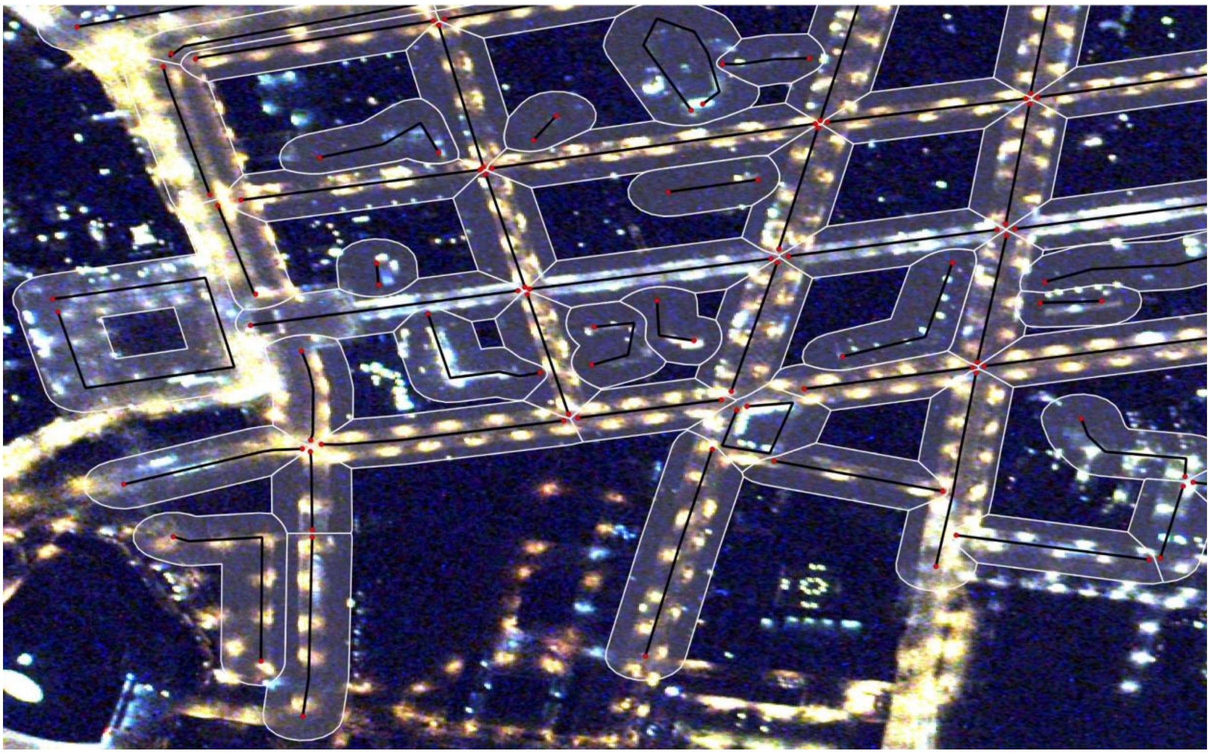

Fig. 14. A comparison of the areas counted in Potsdam's city center to nighttime aerial imagery. The transects shown here are from the bottom leftmost region in Fig. 9, and they are shown with a buffer to indicate the nearby areas. There are some regions with lights between the streets that were likely not counted as part of the surveys.

In developing our 18 light type categories, our aim was to cover all of the most common lighting types, without having so many categories that it would be tedious or difficult to scroll through them all (see 2.2). This means that some types of lights (e.g. flagpole lights) can only be classified as "other" lights. One of the users of the app in North America remarked that the app seemed better suited for use in Europe, and we assume this was at least partially due to the lighting types. These may need to be further refined for international or industrial use. Even within Germany, it can sometimes be difficult to decide between categories (Fig. 15). This is frequently the case for lights installed within a tunnel, or light emissions from a concrete parking structure with multiple levels.

Within our sub-categorizations, we asked participants whether lights had "normal brightness", or were especially bright or dim; this categorization is to some extent subjective, and can be context dependent. For example, we observed that the "house number" lights that appear "normal" on a brightly lit street are often experienced as exceptionally bright if there is little or no ambient lighting around (e.g. on the grounds of residential block buildings). The same subjectivity affects decisions regarding color and the size of illuminated objects. Windows have varied sizes, so it is necessary to approximate the number of "standard sized" windows, and different observers are certain to come to slightly different totals. During the development phase, some of the members of our co-design team strongly advocated for asking participants to decide between 4000 K and 3000 K white light (e.g. "cold" and "warm" white light). We refrained from doing this because we felt that it would be too challenging for most people.

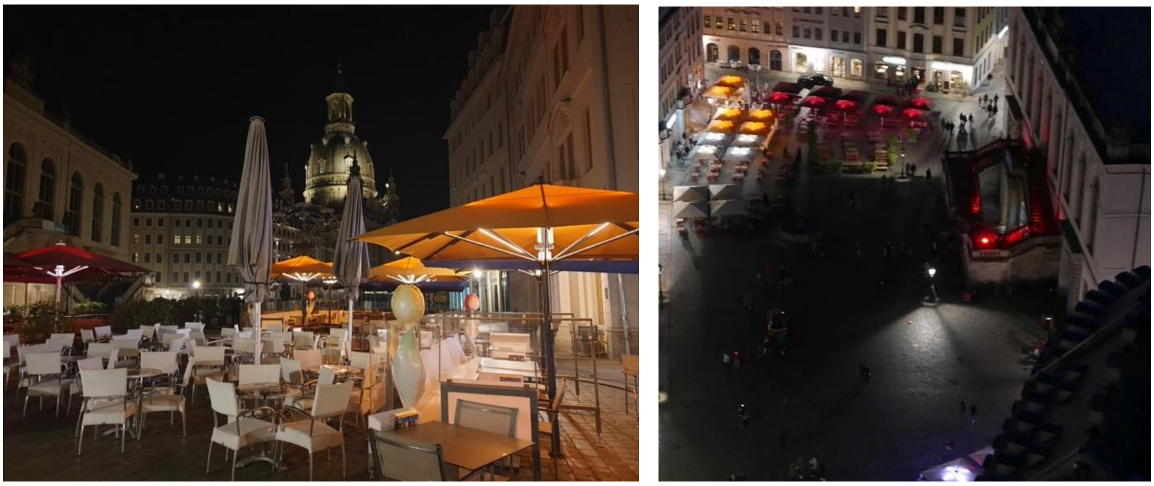

Fig. 15. The lights installed inside the orange umbrellas (left) were categorized by our participants as “canopy lights”, because they were completely covered and shone downward. However, the participants later realized they are actually emitting light upward through the material (right). Photos by Sicco Bauer and Astroclub Radebeul e.V.

Finally, there are several difficulties with using an app in general, and these may be exacerbated by using a progressive web app rather than a native app. While hundreds of people were able to use the app successfully, some of these people had problems at first, and we know that a few people who would have liked to have taken part eventually gave up because they were not able to get the app to work on their device. One issue that frequently caused problems was the need to access their position (both turning on location services for the device itself, and also giving the browser permission to access the location). Having in-person events at the start of a campaign helped with this issue enormously, because it is far easier to work out what the problem is when you can physically handle someone’s device, as opposed to when you can only communicate with them remotely. The vast array of different smartphones, operating systems, and browsers also presents a challenge, as problems can sometimes be unique to the individual device.

In section 2.1, we mentioned that there were limitations to the extent to which the co-design team could influence the research question and methodology. A related critique raised by one of the participants is that there should have been more time devoted to this phase, as well as to a deeper literature review and exchange with the co-design team. In this participant’s view, issues with the comparison to satellite data (especially related to the late overpass time) may have led us to put more effort into ensuring that we took data to understand how lights change over the course of the night. From the perspective of the project organization team, we consider this a valid criticism. In hindsight, the short timeline (set by the funding of the project) limited our ability to fully engage the team, and we agree that a longer period with deeper involvement in the early phases would have improved the project.

6.4. Ideas for future improvement

After the experience of our campaigns, our group identified a number of ways in which the app could be improved. Several of these have already been incorporated into an updated version of the app. Among the more important of these changes are the following: first, it was problematic that participants could not go back and change their answers if after submitting a survey, they immediately noticed a light that they had missed on the first count. We have therefore implemented the possibility to go back and edit the survey within a 10 minute period of the submission in the newest app version. Second, the user-defined transects were based entirely on GPS positions, which can be inaccurate in some cases and lead to transects that don’t cleanly overlay street paths in GIS programs. Our new version of the app allows participants to edit the geometry of transects they themselves created. Finally, the original version of the app checked whether a person was within 50 meters of the starting location of a transect, but did not do a similar check for the finishing point at the end of the survey. In a very small number of cases, we believe that the participants selected the incorrect transect, and saved their survey results on the wrong transect. (We identified this on the basis of the time at which different transects were surveyed in the case of double-counted surveys with large discrepancies in the number and types of lights.)

Thinking longer-term, future versions of this method could potentially incorporate the phone camera to some extent. This could be used, for example, together with a diffraction grating to measure the spectra of specific lights (Burggraaff et al., 2020; Muñoz-Gil et al., 2022), as is done in the Street Spectra citizen science project (García et al., 2020). However, in order to avoid making the method overly cumbersome, we would recommend this should likely only be done for street lights. In the case of illuminated signs, shop windows, and private windows, it is possible that a greatly advanced system could use photogrammetry and radiometry to calculate the lit area and then approximate the luminous (or radiant) flux of these sources.

7. Conclusion and outlook

The Nachtlichter app produces reliable data, and enables the creation of lighting surveys for individual street segments. The active contribution of citizen scientists throughout the project and app design phase contributed strongly to the usability of the final app, and their contribution as surveyors allows the creation of lighting surveys on unprecedented spatial scales. Our group is currently working on an analysis of the data collected in 2021 and 2022, and we expect in a future paper to be able to translate satellite observations in radiometric units (nW/cm^2sr) to more understandable metrics, such as lights/km^2.

In the future, the app could be used for several other scientific purposes. For example, within the German Science Year of 2023 (Wissenschaftsjahr 2023 – Unser Universum) our group will use the app to study how different light types change over the course of the night. This will provide considerable value in interpreting satellite imagery, which is often acquired at a set overpass time. Another possible application is surveying an area in one year, and then returning several years later to see what has changed. This would assist in the interpretation of satellite observations of changes in radiance (Kyba et al., 2017; Sánchez de Miguel, Bennie, et al., 2021). Similarly, the method could be used to study the cause of large differences in radiance from areas of similar population and economic development (Kyba et al., 2015; Falchi et al., 2019). On a more local scale, the app could be used to identify or examine areas that have exceptional light emissions, in order to inform policymakers, or to allow targeted intervention. Relatedly, by examining changes over the course of the night, existing or mandated practices of lighting curfews could be evaluated.

While the development of the app was primarily motivated by scientific questions, the act of co-designing led to the creation of a community. Several of our participants found this to be a welcome diversion from the COVID-19 pandemic, which took place concurrently during our most intensive periods of development. While this is clearly a benefit, we note in closing that at the project's start, the GFZ team had not anticipated the disappointment that many of the community members feel at the prospect of the project ending and the community dissolving. In the opinion of the organizational team, European and German funding structures are currently more focused on the creation of new projects than they are in the maintenance of existing projects, and the communities of expert citizen scientists which these projects foster. Our group succeeded in creating an extremely useful data collection tool, which has the potential to be re-used for exciting additional research. We hope that the app will in the end have a life that goes beyond this initial project.

8. Acknowledgements

This work was funded as part of the Nachtlicht-BüHNE project, funded by Helmholtz Association Initiative and Networking Fund under grant CS-0003. C.C.M.K., H.K., N.S.R, and Y.O.A. acknowledge additional funding from the Helmholtz Association Initiative and Networking Fund under grant ERC-RA-0031, as well as from the European Union's Horizon 2020 research and innovation program under grant agreement no. 689443 via project GEOEssential. C.C.M.K. F.K., L.L.J., and S.M. acknowledge funding from the Nachtlicht-BüHNE im Wissenschaftsjahr 2023 project, funded by the German Federal Ministry of Education and Research (BMBF).

We thank Aidan Melgar, Benjamin Beliveau, Jeffrey Jiyang Wu, and Nicolas Hesel, from WPI and their supervisors for their work in developing the online training tutorial. We thank all the participants of the first Nachtlicht-BüHNE workshop, some of whom did not join the main Nachtlichter organizing team. Finally, we thank all of the citizen scientists who participated in any of the phases of the project, with particular thanks to Florian Distelrath, Irina von Maravic and Peter Stumpf.

8. Dedication

We dedicate this work to the memory of Jiyang "Jeffrey" Wu, who was part of the team of undergraduates that developed the Nachtlichter tutorial in the early part of 2021, and passed away later that year.

References

Aube, M., & Houle, J.-P. (2022). *Building Lighting Device Inventories with the LANcube v2 Open Source Multiangular Radiometer* [Preprint]. EARTH SCIENCES. https://doi.org/10.20944/preprints202210.0485.v1

Bará, S., Bao-Varela, C., & Lima, R. C. (2023). Quantitative evaluation of outdoor artificial light emissions using low Earth orbit radiometers. *Journal of Quantitative Spectroscopy and Radiative Transfer*, *295*, 108405. https://doi.org/10.1016/j.jqsrt.2022.108405

Bará, S., Rodríguez-Arós, Á., Pérez, M., Tosar, B., Lima, R., Sánchez de Miguel, A., & Zamorano, J. (2018). Estimating the relative contribution of streetlights, vehicles, and residential lighting to the urban night sky brightness. In *Lighting Research & Technology* (Issue October 2018). SAGE. https://doi.org/10.1177/1477153518808337

Barentine, J. C., Kundracik, F., Kocifaj, M., Sanders, J. C., Esquerdo, G. A., Dalton, A. M., Foott, B., Grauer, A., Tucker, S., & Kyba, C. C. M. (2020). Recovering the city street lighting fraction from skyglow measurements in a large-scale municipal dimming experiment. In *Journal of Quantitative Spectroscopy and Radiative Transfer* (Vol. 253, p. 107120). Elsevier. https://doi.org/10.1016/j.jqsrt.2020.107120

Bettanini, C., Bartolomei, M., Aboudan, A., Colombatti, G., & Olivieri, L. (2022). Flight test of an autonomous payload for measuring sky brightness and ground light pollution using a stratospheric sounding balloon. *Acta Astronautica*, *191*, 11–21. https://doi.org/10.1016/j.actaastro.2021.11.003

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. In *Journal of Quantitative Spectroscopy and Radiative Transfer* (Vol. 253, p. 107155). Elsevier. https://doi.org/10.1016/j.jqsrt.2020.107155

Burggraaff, O., Perduijn, A. B., Hek, R. F. van, Schmidt, N., Keller, C. U., & Snik, F. (2020). A universal smartphone add-on for portable spectroscopy and polarimetry: ISPEX 2. *Micro- and Nanotechnology Sensors, Systems, and Applications XII*, *11389*, 84–99. https://doi.org/10.1117/12.2558562

Chalfin, A., Kaplan, J., & LaForest, M. (2022). Street Light Outages, Public Safety and Crime Attraction. *Journal of Quantitative Criminology*, *38*(4), 891–919. https://doi.org/10.1007/s10940-021-09519-4

Cleaver, O. P. (1943). Control of Coastal Lighting in Anti-Submarine Warfare. In *Technical Report ADA954894*. https://apps.dtic.mil/dtic/tr/fulltext/u2/a954894.pdf

Collins, H. M. (1988). Public Experiments and Displays of Virtuosity: The Core-Set Revisited. *Social Studies of Science*, *18*(4), 725–748. https://doi.org/10.1177/030631288018004006

Dobler, G., Ghandehari, M., Koonin, S. E., Nazari, R., Patrinos, A., Sharma, M. S., Tafvizi, A., Vo, H. T., & Wurtele, J. S. (2015). Dynamics of the urban lightscape. In *Information Systems* (Vol. 54, pp. 115–126). https://doi.org/10.1016/j.is.2015.06.002

Eitzel, M. V., Cappadonna, J. L., Santos-Lang, C., Duerr, R. E., Virapongse, A., West, S. E., Kyba, C. C. M., Bowser, A., Cooper, C. B., Sforzi, A., Metcalfe, A. N., Harris, E. S., Thiel, M., Haklay, M., Ponciano, L., Roche, J., Ceccaroni, L., Shilling, F. M., Dörler, D., … Jiang, Q. (2017). Citizen Science Terminology Matters: Exploring Key Terms. *Citizen Science: Theory and Practice*, *2*(1), Article 1. https://doi.org/10.5334/cstp.96

Elvidge, C. D., Baugh, K. E., Kihn, E. A., Kroehl, H. W., & Davis, E. R. (1997). Mapping city lights with night-time data from the DMSP operational linescan system. In *Photogrammetric Engineering and Remote Sensing* (Vol. 63, Issue 6, pp. 727–734). American Society for Photogrammetry and Remote Sensing.

Elvidge, C. D., Zhizhin, M., Ghosh, T., Hsu, F.-C., & Taneja, J. (2021). Annual Time Series of Global VIIRS Nighttime Lights Derived from Monthly Averages: 2012 to 2019. *Remote Sensing*, *13*(5), Article 5.

https://doi.org/10.3390/rs13050922
EnSikuMaV - Verordnung zur Sicherung der Energieversorgung über kurzfristig wirksame Maßnahmen, Pub. L. No. Kurzfristenergieversorgungssicherungsmaßnahmenverordnung vom 26. August 2022 (BGBl. I S. 1446) (2022). https://www.gesetze-im-internet.de/ensikumav/BJNR144600022.html
Falchi, F., Furgoni, R., Gallaway, T. A., Rybnikova, N. A., Portnov, B. A., Baugh, K., Cinzano, P., & Elvidge, C. D. (2019). Light pollution in USA and Europe: The good, the bad and the ugly. In *Journal of Environmental Management* (Vol. 248, p. 109227). Elsevier. https://doi.org/10.1016/j.jenvman.2019.06.128
García, L., Zamorano, J., González, R., González, E., Corcho, O., Gomez, J., Christobal, G., Izquierdo, J., Sanchez, A., Tapia, C., Gallego, J., & Pascual, S. (2020). *ACTION Street Spectra citizen science project*. Artificial Light at Night, online conference. https://guaix.ucm.es/wp-content/uploads/2020/06/eALAN_Street_Spectra_Luci%CC%81a_Garci%CC%81a.jpg)
GFZ. (2021). *We count lights because the night counts.* https://www.gfz-potsdam.de/en/press/news/details/we-count-lights-because-the-night-counts
Hale, J. D., Davies, G., Fairbrass, A. J., Matthews, T. J., Rogers, C. D. F., & Sadler, J. P. (2013). Mapping lightscapes: Spatial patterning of artificial lighting in an urban landscape. In *PloS one* (Vol. 8, Issue 5, p. e61460). https://doi.org/10.1371/journal.pone.0061460
Hänel, A., & Kunzemann, T. (2021). The fraction and change of public lighting in Preussisch-Oldendorf, Germany. *ALAN 2021 Conference Abstract Booklet*, 16–17.
Hiscocks, P. D., & Gudmundsson, S. (2010). The Contribution of Street Lighting to Light Pollution. In *Journal of the Royal Astronomical Society of Canada* (Vol. 104, Issue 5, p. 190).
Kuechly, H. U., Kyba, C. C. M., Ruhtz, T., Lindemann, C., Wolter, C., Fischer, J., & Hölker, F. (2012). Aerial survey and spatial analysis of sources of light pollution in Berlin, Germany. In *Remote Sensing of Environment* (Vol. 126, pp. 39–50). https://doi.org/10.1016/j.rse.2012.08.008
Kyba, C. C. M., Garz, S., Kuechly, H., de Miguel, A., Zamorano, J., Fischer, J., & Hölker, F. (2015). High-Resolution Imagery of Earth at Night: New Sources, Opportunities and Challenges. In *Remote Sensing* (Vol. 7, Issue 1, pp. 1–23). https://doi.org/10.3390/rs70100001
Kyba, C. C. M., Kuechly, H., Longejans, L., Schulte-Römer, N., Öner Altıntaş, Y., & Nachtlichter Co-design Team. (2023). *Methods and data of citizen science project Nachtlichter* [dataset]. https://doi.org/10.5880/GFZ.1.4.2023.002
Kyba, C. C. M., Kuester, T., Sánchez de Miguel, A., Baugh, K., Jechow, A., Hölker, F., Bennie, J., Elvidge, C., Gaston, K., & Guanter, L. (2017). Artificially lit surface of Earth at night increasing in radiance and extent. *Science Advances*, *3*(11), e1701528. https://doi.org/10.1126/sciadv.1701528
Kyba, C. C. M., Ruby, A., Kuechly, H. U., Kinzey, B., Miller, N., Sanders, J., Barentine, J., Kleinodt, R., & Espey, B. (2021). Direct measurement of the contribution of street lighting to satellite observations of nighttime light emissions from urban areas. *Lighting Research & Technology*, *53*(3), 189–211. https://doi.org/10.1177/1477153520958463
Li, X., Levin, N., Xie, J., & Li, D. (2020). Monitoring hourly night-time light by an unmanned aerial vehicle and its implications to satellite remote sensing. In *Remote Sensing of Environment* (Vol. 247, p. in press). https://doi.org/10.1016/j.rse.2020.111942
Li, X., Zhao, L., Li, D., & Xu, H. (2018). Mapping Urban Extent Using Luojia 1-01 Nighttime Light Imagery. In *Sensors (Basel, Switzerland)* (Vol. 18, Issue 11). https://doi.org/10.3390/s18113665
Luginbuhl, C. B., Duriscoe, D. M., Moore, C. W., Richman, A., Lockwood, G. W., & Davis, D. R. (2009). From the Ground Up II: Sky Glow and Near-Ground Artificial Light Propagation in Flagstaff, Arizona. In *Publications of the Astronomical Society of the Pacific* (Vol. 121, Issue 876, pp. 204–212). https://doi.org/10.1086/597626
Miller, S., Straka, W., Mills, S., Elvidge, C., Lee, T., Solbrig, J., Walther, A., Heidinger, A., & Weiss, S. (2013). Illuminating the Capabilities of the Suomi National Polar-Orbiting Partnership (NPP) Visible Infrared Imaging Radiometer Suite (VIIRS) Day/Night Band. In *Remote Sensing* (Vol. 5, Issue 12, pp. 6717–6766). https://doi.org/10.3390/rs5126717
Muñoz-Gil, G., Dauphin, A., Beduini, F. A., & Sánchez de Miguel, A. (2022). Citizen Science to Assess Light Pollution with Mobile Phones. *Remote Sensing*, *14*(19), Article 19. https://doi.org/10.3390/rs14194976
Nachtlicht-BüHNE. (2023). *Nachtlicht-BüHNE project website*. Nachtlicht-BüHNE. https://nachtlicht-buehne.de/
Ruhtz, T., Kyba, C. C. M., Posch, T., Puschnig, J., & Kuechly, H. (2015). *Lichtmesskampagne Zentralraum*

Oberösterreich [Aircraft data acquisition report]. https://www.land-oberoesterreich.gv.at/Mediendateien/Formulare/Dokumente%20UWD%20Abt_US/us_strahlen_Endbericht_Lichtkataster_20151126_Linz_Final.pdf

Sánchez de Miguel, A., Bennie, J., Rosenfeld, E., Dzurjak, S., & Gaston, K. J. (2021). First Estimation of Global Trends in Nocturnal Power Emissions Reveals Acceleration of Light Pollution. *Remote Sensing*, *13*(16), Article 16. https://doi.org/10.3390/rs13163311

Sánchez de Miguel, A., Zamorano, J., Aubé, M., Bennie, J., Gallego, J., Ocaña, F., Pettit, D. R., Stefanov, W. L., & Gaston, K. J. (2021). Colour remote sensing of the impact of artificial light at night (II): Calibration of DSLR-based images from the International Space Station. *Remote Sensing of Environment*, 112611. https://doi.org/10.1016/j.rse.2021.112611

Schulte-Römer, N., Bauer, S., Fischer, D., Klan, F., Kuechly, H., Mattern, J., Sulzer, G., Weiß, E., Zschorn, M., & Kyba, C. C. M. (2023). *Wir zählen Lichter, weil die Nacht zählt. Transdisziplinäre Zusammenarbeit im Nachtlicht-BüHNE Projekt*. Deutsches GeoForschungsZentrum GFZ. https://doi.org/10.48440/gfz.b103-23036

Stare, J., & Kyba, C. (2019). *Radiance Light Trends* (p. 5 Files) [Application/octet-stream,application/octet-stream,application/octet-stream,application/octet-stream,application/octet-stream]. GFZ Data Services. https://doi.org/10.5880/GFZ.1.4.2019.001

Sullivan, W. T. (1989). A 10 km resolution image of the entire night-time Earth based on cloud-free satellite photographs in the 400–1100 nm band. *International Journal of Remote Sensing*, *10*(1), 1–5. https://doi.org/10.1080/01431168908903843

Walczak, K., Wisbrock, L., Tarr, C., Gyuk, G., Amezcua, J., Cheng, C., Cris, J., Jimenez, C., Mehta, M., Mujahid, A., Pritchard, L., Suquino, K., & Turkic, L. (2023). Quantifying nighttime light emission by land use from the stratosphere. *Journal of Quantitative Spectroscopy and Radiative Transfer*, *310*, 108739. https://doi.org/10.1016/j.jqsrt.2023.108739

Wuchterl, G., & Reithofer, M. (2017). *Licht über Wien V*. http://kuffner-sternwarte.at/2018/Studie_Lichtverschmutzung_Wien_2011-2017.pdf

Zschorn, M., & Mattern, J. (2022, June). Counting lights for Sustainability – Insights from the Citizen Science Project Nachtlicht-BüHNE. *Proceedings of Science*. Austrian Citizen Science Conference 2022. https://pos.sissa.it/407/003/pdf

Appendix

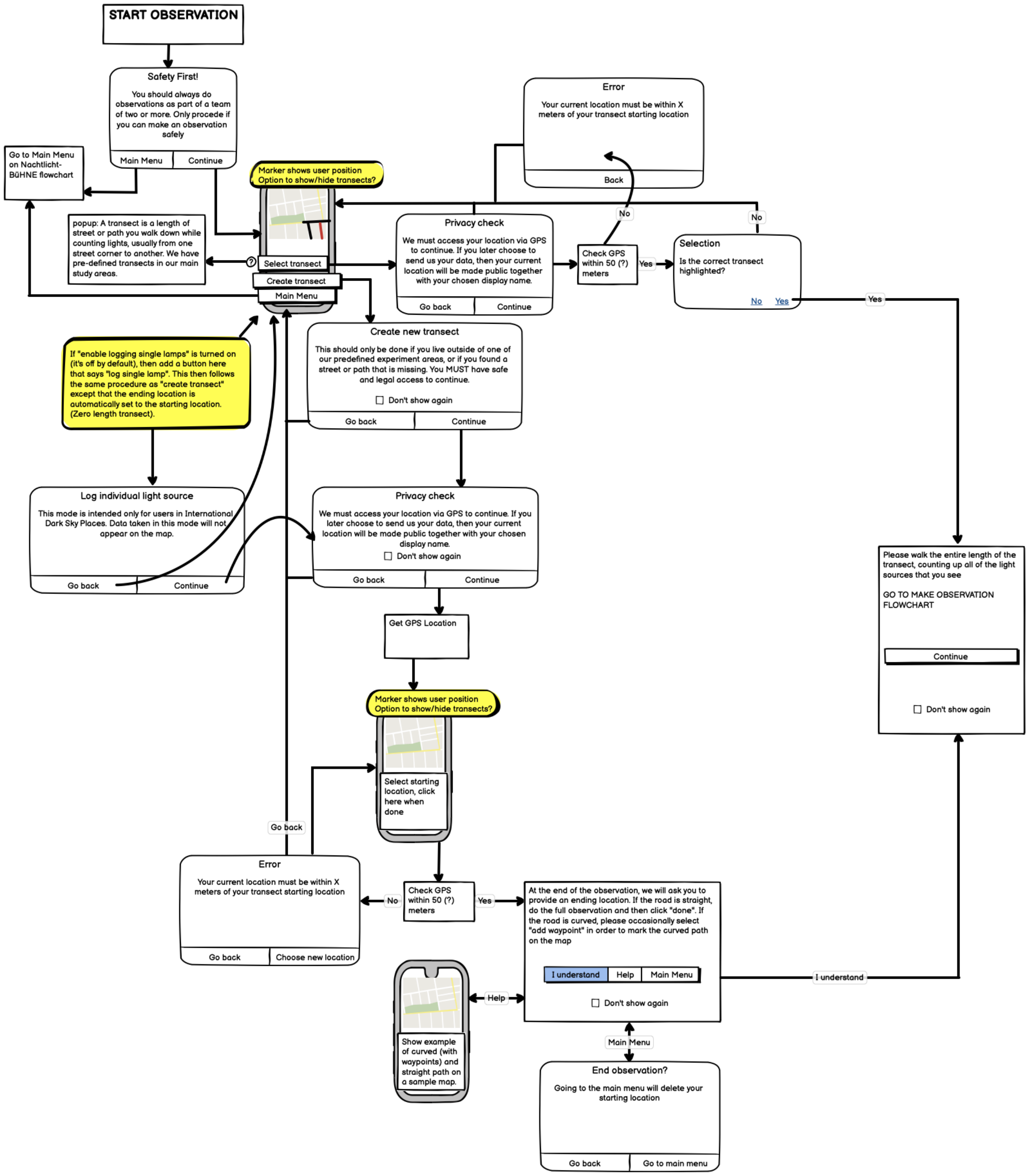

Fig. A1. One example from the set of six flowcharts our group created and provided to the developer.