Drone based analysis of nocturnal light pollution

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ABSTRACT:

To obtain a comprehensive understanding of a municipality's nocturnal light pollution, various remote sensing tools are available. From the drone's perspective, small areas, i.e., a few hectares can be recorded, mapped, and quantified with regard to their illuminance and luminance. Commercially available RTK-GNSS drones, which are commonly used in the surveying sector, are able to quantify night-time light pollution with the help of so called "light control points" (LCP). Via regression techniques the measured luminance at LCP's is transferred to the orthomosaic. Since it is possible to fly at different times, it is possible to answer various questions about the specific nocturnal light pollution and, if necessary, the lack of light, which are of importance in municipal decision processes for urban infrastructure lightning. Radiometric calibration of a commercial drone camera is a difficult task. Preliminary results showed a complex behaviour of the camera, which requires further investigations.

1. Introduction to nocturnal light pollution

The term light pollution, also known as light smog or light contamination, has increasingly come into focus in recent years e.g. Chepesiuk, (2009), Miller et al. (2017). Unfortunately, the term light pollution has a negative connotation., Schulte-Römer et al. (2019) and there is no accepted threshold value for what constitutes light pollution. Nevertheless, it is clear, that artificial lights emitting upwards during the night hours mainly cause the nocturnal light pollution, see figure 1.

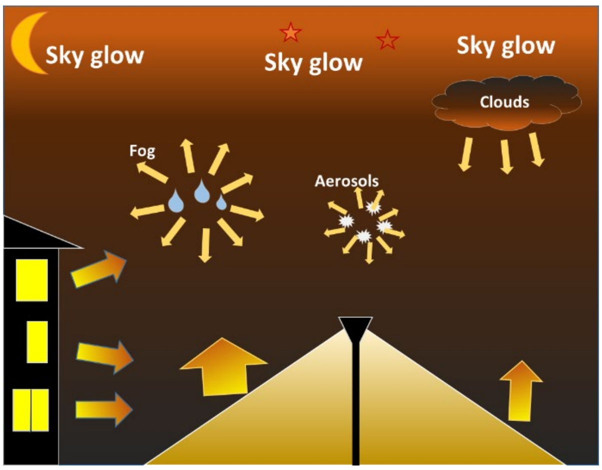

Figure 1. Emergence of the urban light dome (skyglow): Artificial light is emitted upwards and scattered by clouds, water droplets and aerosols. From the ground it looks as if the sky is glowing, modified after Kaltenegger 2018.

In sum, the scattered light from the many individual sources leads to a brightening of the lower atmosphere (sky glow), i.e. it is no longer totally dark at night. The lack of darkness has numerous disturbing influences, Bollinger et al. (2020), Contín et al. (2016), Schroer et al. (2019):

- On fauna, for example on nocturnal flying insects, van Grunsen et al. (2020) or birds that have specialised in nocturnal insect food.
- Plants can be additionally stressed by nocturnal light, Meravi et al. (2020). Nocturnal light interferes in various ways with the photosynthetic activities or the daily and annual rhythms of plants. The additional stress can influence phenological development, lead to reduced growth, etc.
- In general, even very low light levels of 0.05 lx can have an impact on the internal clock of birds and influence their circadian rhythm, de Jong et al. 2016). This also applies in a similar way to mammals, Grubisic et al. (2019) and thus also to humans, in that artificial light changes the melatonin level, which can lead to increased insomnia in humans, e.g. Kumar et al. (2019).
- Astronomical observations of the night sky are limited in cities. For example, the Milky Way is no longer visible in cities and their suburban surroundings. This is particularly true in Germany, Falchi et al. (2016).

This latter effect can also be utilised to approximate the light pollution at a location. On the other hand, nocturnal light is indispensable for a city, it enables urban life, prevents accidents and can also be identity-forming for a city, e.g. in the form of illuminations of monuments, bridges etc. The nocturnal light load of a city has many faces and varies spatially and temporally very strongly. Before technical and administrative measures are taken to reduce unwanted light pollution or minimize future changes, a careful assessment of the current situation is necessary.

Artificial night-time lighting is primarily used to illuminate public spaces. In this context, there are of course also regulations and standards that govern the lighting of roads and paths, for example. In the currently valid standard (DIN EN 13201, 2016), higher-level roads, road junctions, road junctions and marked crosswalks are illuminated more strongly than side streets or residential streets. For drivers, the uniformity of luminance is important for the perception of vehicles, people and objects on or close to the road. If areas are very unevenly illuminated, obstacles or pedestrians cannot be seen due to insufficient contrast against a dark background. There are also regulations that deal with glare inside the home caused by external light sources. Irrespective of this, measuring and checking the above regulations is time-consuming and sometimes unrealistic in practice. Therefore, in addition to terrestrial measurements, night-time drone flights can be used to measure luminance or light exposure quite elegantly.

This article presents two different approaches to quantifying night-time light pollution using a drone. The first paragraph presents an indirect approach in which the luminance is measured at selected points with the help of so-called "light control points" and applied to the image area via regression. The basic prerequisite for this is high-precision georeferencing, which requires a drone equipped with high-precision GNSS. Images taken at different points in time then make it possible to observe changes. The second part of the article deals with the radiometric calibration of a commercial drone camera. Finally, the two approaches are compared.

1.1 Measuring photometric quantities of light – illuminance and luminance

There are two different ways of measuring light. The radiation-physical or radiometric quantities and the photometric quantities (CIE 2019). The radiometric quantities are commonly used for remote sensing applications. In the context of light pollution, however the most relevant photometric parameters are the photometric parameters, which are measured according to the standardized brightness perception of the human eye. If the irradiated area is considered, irradiance (*Ee*) and illuminance (*Ev*) are used to indicate how much radiation per area reaches the light source. Luminance is the photometric analogy to radiance (*Le*). In photometry, luminance (*Lv*) is a measure of how much light is emitted or reflected from a surface, per unit area. The unit of measurement is candelas per square meter (cd/m²).

2. Night time drone surveys – how does it work?

The nocturnal light pollution of individual objects and neighbourhoods cannot be answered with satellite image analysis, since this does not provide information about individual light sources due to the too coarse spatial resolution. Here, a different technology is needed. In addition to experimental solutions, e.g. stratospheric balloons without their own propulsion, which can provide large-area night images with a ground resolution of approx. 10m/pixel, Gyck et al. (2021), aerial surveys by surveying aircraft, e.g. Kuechly et al. (2012) or drones are the means of choice. Drones have been used in different ways to explore nocturnal lights. Bobkowska et al. 2024 used a drone as a carrier platform for various sensors. The payload consists of a radiometrically calibrated camera, a spectrometer, a sky quality meter and a multispectral camera. A luminance map was created using the images from the radiometrically calibrated camera. A terrestrial validation of the luminance values determined from the drone images was not carried out. Massetti et al. (2022) used a real-time comparison between the mean luminance measured with a Sky Quality Meter (SQM) from the drone and images taken in parallel to determine the brightness. Terrestrial luminance measurements taken in parallel confirm a qualitative relationship. Li et al. (2020) took a different approach to determine the change in nocturnal light pollution over a period of several drone images and parallel SQM measurements. Correlations of the RGB values of the drone recordings with stationary and mobile SQM measurements showed clear correlations that allow the RGB values to be converted into luminance values

Interestingly, there are no specific legal regulations for night time drone flights. According to the EU Drone Regulation 2019/945, they are simply permitted if a certified drone (C0 - C6) is used. These drones must have suitable lighting in order to be recognized by other air traffic participants at night. Nevertheless, night flights are more complex to plan and carry out than daytime flights. For example, the sensors for obstacle detection do not work or only work to a very limited extent. This means that the take-off and landing sites must be explored in daylight and complex flight maneuvers should be avoided, as the drones often have to be flown partly by hand. Independently of this, all rules of the EU Drone Regulation and additional national rules, such as the German LuftVO apply. Therein a large number of geographical restrictions for drone flights in urban areas exist, e.g. minimum distances to industrial areas, rail roads, administrative buildings etc. This makes drone flights in the open category over built-up areas particularly complicated, figure 2 .

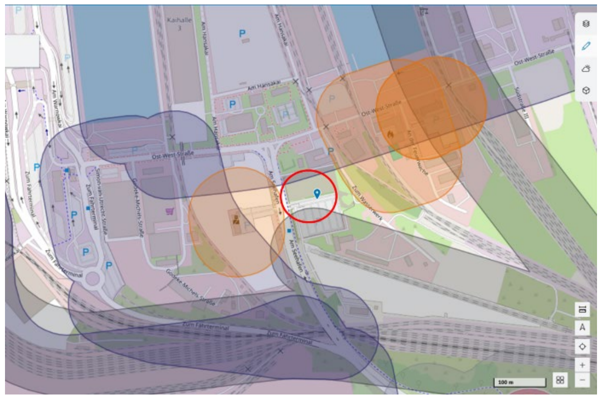

Figure 2: Detail of the official restricted geographical areas map for the harbour of the city of Rostock (Source: Dipul Map Tool)

Due to the maximum flight height of 120 m in the open category, drones are generally not suitable to cover a large city like Rostock with an area of 100 km². Rather, they are ideally suited to cover smaller areas or to map individual objects. Due to the long exposure times, the drone must remain still during a shot, which can be best achieved with little or no wind. This additionally reduces the areal performance. Together with the multitude of airspace restrictions, panoramas of different parts of the city are often the only option to cover a larger area of several km² around the respective location, even if only obliquely. Due to the oblique perspective, the drone data are not directly comparable to satellite data. Rather, in the oblique perspectives, the light from the windows facing the camera can also be observed. Since drone images can be taken even when the sky is cloudy, they are more accurate and more flexible to use for municipal issues. Drone images can be repeated at different times during the night to document changes of the light pollution during the night.

From a practical perspective there are several special aspects to consider when carrying out night time surveys with a drone:

1. with an overall dark background, the exposure time etc. must be adapted to the lighting situation so that less bright areas can also be depicted. Long exposure times, on the other hand, harbor the risk of blurred images.
2. wind, especially gusty wind, should be avoided during the drone flight in order to achieve sharp images with exposure times of 1 - 3 seconds.
3. strong light sources can be overexposed and outshine their surroundings.
4. increasing the ISO value leads to image noise, which is problematic with dark images. ISO values of 400 – 640

provide a reasonable signal to noise ratio, even in darker areas.
5. it is usually necessary to post-process the images (contrast manipulation) in order to be able to correctly reproduce the differences in brightness. The images should therefore be taken in RAW format. Additionally, the RAW images provide the user with the full 12-bit radiometric range of modern drone cameras.
6. Systematic drone flights of small areas may be triggered manually, as the drone must remain in the air for a short time to take a picture and then fly on to the next point. This means that a night-time image flight with one battery can cover a much smaller area than during the day.
7. Since a high ground resolution is rarely necessary, the maximum flight altitude of 120 m can be used to optimize the areal coverage. The flight altitude of 120 m has a further advantage, as the noise level of the aircraft decreases with increasing flight altitude. Thus the sound of the drone often disappears behind the traffic noise in the city. Last but not least, this flight altitude can also be used to claim an exemption from the German LuftVO, § 21h. Thereby overflights over residential areas are allowed under special circumstances at an altitude of 100 - 120 m.
8. if a drone is equipped with an RTK option, orthomosaics with a high geometric quality of a few centimeters are quite easy to create Przybilla et al., 2020, otherwise illuminated ground control points are required for precise georeferencing.

2.1 Night time drone surveys of the University campus

On February 28th, and March 20th 2024, two nighttime drone flights with a Mavic 3 enterprise drone (M3E, DJI, Shenzhen, China) were conducted over the faculty of agricultural and environmental sciences (AUF), which covers approximately 6 ha. At an altitude of 120 m, a total of 42 and 32 images respectively were manually triggered at previously defined locations in three flight strips. The transverse and longitudinal overlap is about 70% / 70%. The exposure time for the first flight was set to 3.2s with an ISO value of 400. Due to the partial overexposure the exposure time was reduced to 1.3s for the second flight. The first flight was conducted before 21:00 (figure 3) and the second flight after 21:00 (figure 4), the time at which the local supermarket and the buildings of the university are closed.

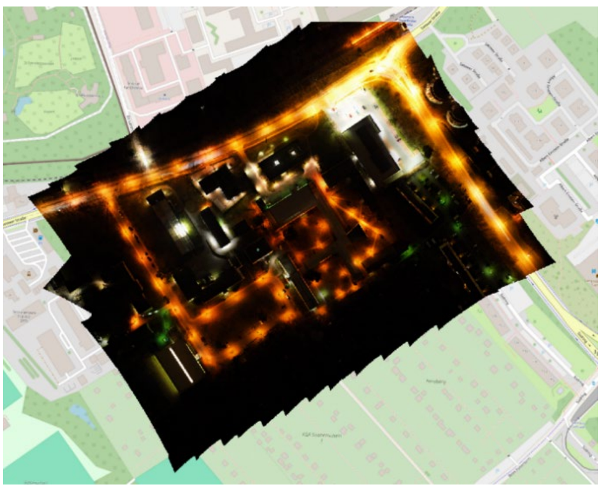

Figure 3. Nighttime orthophoto mosaic from campus of agricultural and sciences (AUF), 28/2/2024 (20:20-20:32), derived from 42 images

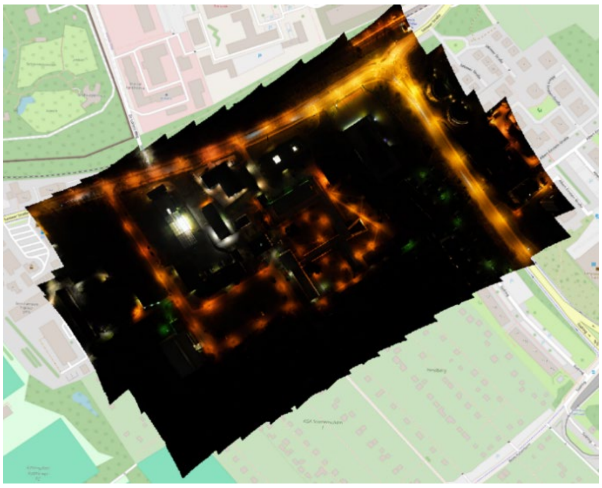

Figure 4: Nighttime orthophoto mosaic from campus of agricultural and sciences (AUF), 20/3/2024 (21:16-21:26), derived from 32 images

The calculated ground resolution (GSD) is 3 cm / pixel. The geometric resolving distance (GRD) which is defined to be the value that reflects the sensor's ability to resolve fine details, is lower than the GSD. The GRD in influences by atmospheric conditions, image quality etc. Despite daytime imagery, for which the GRD is considered to be constant within the image, the GRE in night time images differs quite significantly within an image and between images. The GRE or the image quality, is significantly lower in dark areas, than in bright areas of the imagery. Additionally, image blur, due to the long exposure time adds to differences in the GRE between the images.

The images were subsequently processed into an orthomosaic using Photoscan Metashape (Agisoft LLC) 2.0.8. software. From a photogrammetric point of view, it is important to mention, that the quality and the completeness of the point cloud is of way lower quality than for day time drone survey. This applies in particular to buildings and their roofs, which are usually among the darkest areas of the images. In order to nevertheless ensure a precise image of the building edges, a DOM of an existing drone flight can be used. The geometric accuracy of the block without any ground control, determined with 11 man holes in the vicinity of street lamps which served as check points, was 5.2 cm for the February 28th survey and 4.5 cm for the survey on March 20th.

2.2 Drone based illuminance / luminance mapping using "light control points"

Street lamps produce a typical cone of brightness that becomes increasingly darker towards the edge. With vertical images it is in principle possible to calibrate the drone data radiometrically and thus also to quantify the differences in brightness. Therefore, the illuminance as well as the luminance is measured at several points with well-known geographic coordinates (=light control points, LCP's). The LCP's are measured over spots with homogeneous illumination. Therefore, they are not suited to support georeferencing. The illuminance / luminance of the orthomosaic is determined via a regression analysis against the ground observations at the light control points. The measurement of the illumination is a compromise, because

1. the brightness (=grey values) measured in the aerial photograph corresponds in reality to the radiation reflected from the ground (= luminance). The luminance depends on the illumination and on the specific reflection properties of

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the surface. The reflectance of different surfaces varies considerably and is also dependent on wavelength and the viewing angle in several respects.

2. The illuminance of the street lighting, which is well measurable for the experiment, varies not only in the position, but by definition also with the height at which the illuminance is measured. For example, the illuminance near a street lamp on the ground is only about half of that measured at a height of 1.5 m, which corresponds to eye level. The measurement of illuminance with the lux meter is hemispherical, i.e. the measurement depends on the distance to one or more light sources and the ambient light.

The night is illuminated by various light sources with different spectral properties. As far as street lighting is concerned, sodium vapor lamps are predominant and LED lights are also becoming increasingly common. These in turn have different color temperatures, so that the illuminated areas in the images sometimes appear in green, neutral, i.e. white or even blue tones. The light control points were selected in the vicinity of two street lamps as well as in the vicinity of the greenhouse. The precise positions of the 48 light control points were measured in advance with a Leica GS7 RTK GNSS receiver. The luminance and the illuminance of the individual points was measured. The illuminance was measured at the ground with a lux meter (C.A. 1110 Chaivin Arnoux). The luminance was measured with the Sky Quality Meter (SQM-L) from Unihedron from a height of approx. 1.5 m towards the ground. The sensor's aperture angle of 20° results in a ground spot with a diameter of 0.52 meters. This means that the luminance is then averaged over the resulting area of 0.21 m². The SQM is a measuring device originally developed for measurement of the brightness of the sky in magnitudes per square arc second (mag/arcsec²), Fiorentin et al., (2022). The measured variable can be converted into a luminance L_v (cd/m²) for a measured value according to the manufacturer's specifications using equation 1:

$$L_v = 10.8 \times 10^4 \times 10^{\left(-0.4 \times \frac{m}{\frac{mag}{aecsec}^{2}}\right)} \quad (1)$$

The green wavelength range is particularly suitable for two reasons. Firstly, it reproduces approx. 70 % of the spectral sensitivity of human vision, Massetti et al., (2022) and secondly, it does not saturate in the drone images even with very bright light sources. A comparison of the illumination and the luminance at the light control points underlines, that both approaches measure similar, but not identical light phenomena, figure 5.

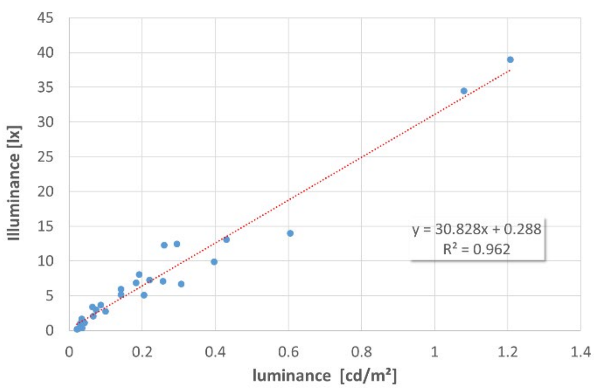

Figure 5. Measured hemispherical illumination (lux meter) in relation to luminance measurements (SQM-L) from the ground taken on 28/2/2024 at "LCP's" [n = 48].

For further conversion of the color orthomosaic into luminance values, the green band from orthomosaic was extracted to a gray scale image. The reason for this is that the light from the sodium vapor lamps is mainly found in the red and green wavelength ranges and less in the blue wavelength range.

The gray values of the individual light control points were extracted from the image and plotted against the measured luminance, figure 6. As can be seen from the graph, there is a non-linear relationship between the gray values and the measured luminance values. The luminance values increase logarithmically with the gray values.

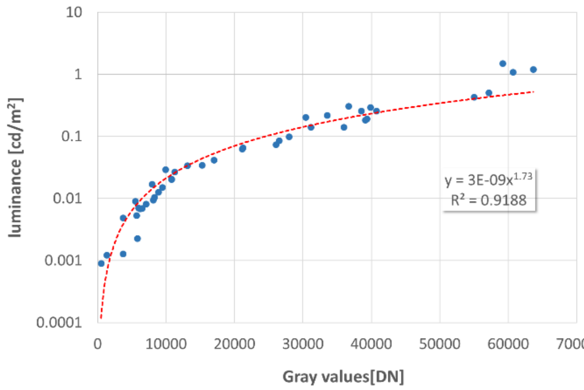

Figure 6. Grey values of green band (RAW) in relation to the measured luminance at 46 "LCP's" of the 28/02/2024 night-time image of AUF

Since the focus is on the illumination situation around the street lamps, it is worth taking a closer look at the range from 0.2 - 10 lx, which equates to a luminance of 0.006 – 0.3 cd/m², Figure 10. At this level, the illuminance also increases exponentially with the gray values. The observed scatter is due to the different reflective properties of the substrates (road surface, lawn, etc.) as well as to the different illuminance of the lanterns. The road surface of the measurement series around lamp 1 and 3 is dark cobblestone. The measured illumination values of the measurement series "Lamp 2" are from a pedestrian walkway with light-colored slabs, except for one value directly under the lantern. The measured illumination values of the LED lighting at the pedestrian walkway of the glass house seem to result in brighter gray values. However, the slabs are also about as bright as the pedestrian walkway at lamp 2.

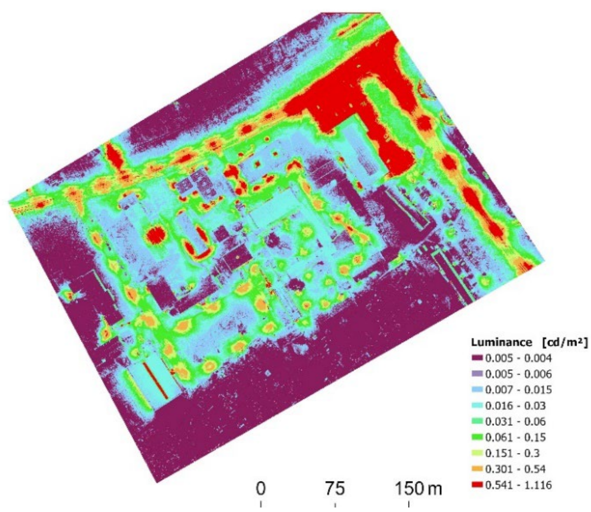

Figure 7. Night time luminance map based on drone flight of the campus area AUF on 2/28/2024 (20:20 - 20:32) and reference luminance measurements.

When visualizing the results, it should be noted that the luminance values cover a very wide range of values, ranging from 0 – 1.1 cd/m². Since the value range of 0.006 – 0.3 cd/m² is of great relevance for street lighting, this value range is stretched for the visualization, Figure 7 and Figure 8.

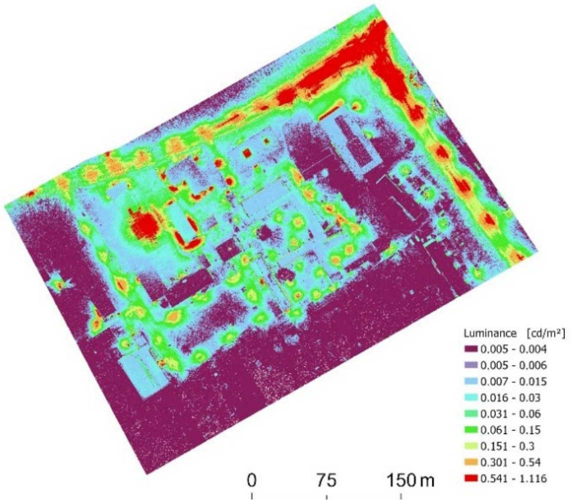

Figure 8. Night time luminance map based on drone flight of the campus area AUF on 3/20/2024 (21:16 - 21:26) and reference luminance measurements

2.3 Changes of nocturnal lights

Nocturnal light exposure varies from night to night and also within the night. There are several reasons for this, e.g. changing moon phases and/or nocturnal cloud cover, Kyba et al. 2015. As a result, urban light is scattered in various ways in the lower atmosphere and partially reflected back to the ground. The intensity of human activities and the associated light requirements also fluctuates throughout the night, e.g. Li et al. (2020), Meier (2018). The latter aspect in particular is of great importance for light planning and light design in a municipality.

In order to record and assess the extent of the differences in night-time light pollution, two time periods were compared with each other. On the one hand, it was investigated whether and to what extent store opening times and the closing of buildings have an impact on night-time light pollution, see Figure 10, and on the other hand, how light pollution changes over a period of several years and what the changes then mean, Figure 11.

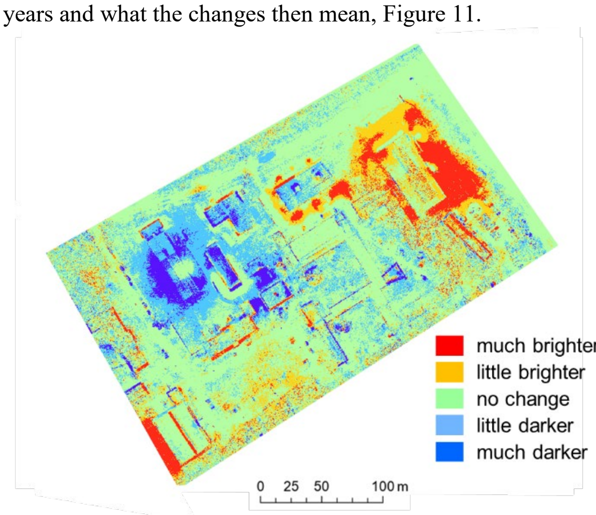

Figure 9. short term changes in luminance of nocturnal light sources – difference between image acquired at 28/2/2024 (20:20-20:32) and 20/3/2024 (21:16-21:26)

The change map shows that the parking lot in front of the supermarket is brightly lit before 21:00. The same applies to the lighting around the buildings and the sports hall. The sharp decrease in brightness is due to an experiment in the glasshouse. Plants are illuminated there for a variety of experiments.

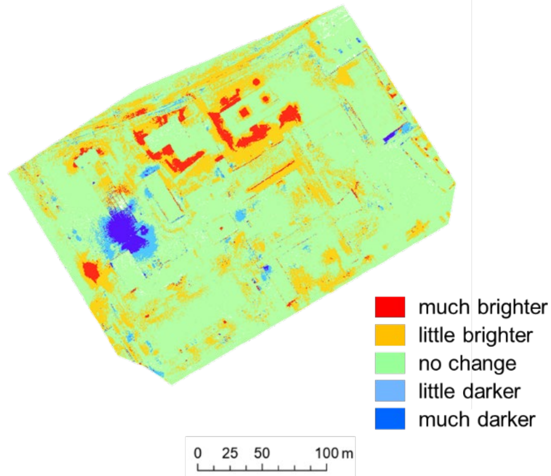

Figure 10. long term changes in luminance of nocturnal light sources – difference between 21.03.2022 and 28.02.2024

Strong changes in brightness are related to new buildings and added light sources that illuminate the direct surrounding of these buildings. Also a street lamp that shines again creates strong changes. Smaller changes in the luminance are caused by replaced light sources of the street lights. Small reductions in the luminance are causes by dirty lamps or aged light bulbs, emitting less light. Strong reductions are observed, once the light sources don't not light up.

3. Radiometric camera calibration

Recent scientific publications, Li et al., (2020) have shown that images of conventional commercial drones can also be used very well in order to quantify the observed brightness. This is not surprising, after all, there is basically a (log)linear relationship between the gray values of a CCD sensor and the light intensity. For daytime imagery the focus of radiometric calibration is often on the correct color response, Martinez, (2007). However, this is of secondary importance when measuring light at night, e.g. when using fisheye lenses for the hemispherical measurement of light pollution, Jerchow et al. (2017). The radiometric calibration of an RGB cameras a complex procedure that covers several aspects, e.g. bias and dark current behavior, noise, vignetting and other aspects, Fiorentin, et al. (2020).

Compared to industrial cameras, the calibration of commercial drone cameras is more demanding, because they only provide a few setting options for the user and the manufacturers provide very little information about the radiometric properties of the camera. Additionally, color balancing and other corrections are made internally in the camera over which the user has little to no influence.

One challenge when calibrating a camera for measuring nocturnal luminance is to find luminance measuring devices that are capable of measuring very low luminance levels (Hänel et al., 2018). Commercially available devices for spot measurement of luminance are capable of measuring down to 0.01 cd/m² with sufficient accuracy. Expensive CMOS imaging photometers have a wider measuring range, capable of measuring luminance down to 0.0001 cd/m².

The calibration approach presented below does not claim to be a complete, comprehensive radiometric calibration. Rather, it is focused on the application scenario of nighttime drone images. For this reason, various simplifications are made during calibration, e.g. the vignetting of the camera is not taken into account, as only the central part of the image is used for orthomosaics. The calibration refers only to the green wavelength range, one aperture/ISO combination and three different exposure times. Temperature-dependent influences are not modeled, nor are different gain settings.

The Powermeter Model 1918 was the only measuring device available for the proposed radiometric calibration. This device however, only measures the energy and power of a monochromatic light source in radiometric quantities. As the green colour channel contributes more than 71 % to the luminosity of an RGB image, a filter with a width of 4 nanometres and a maximum at 532 nanometres was selected. The luminance to be measured depends on the luminous flux of the radiation source and the size of the light source projected onto a surface. Therefore, the green light was projected on a Plexiglas disc at a distance of 140 mm to the light source. At this distance the diameter of the projected light source is 75 mm. Different luminance (Lv) values were generated by changing the current (= luminous flux) of the light source, Figure 11.

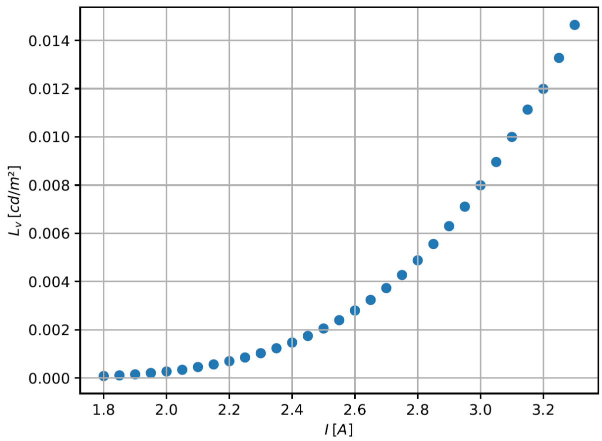

Figure 11. Calibration curve of the light source

For the calibration experiment an ISO value of 400 and an aperture value of 3.2 were used for the test series, as these proved to be suitable when taking night time images. Test series with different luminance values were carried out with exposure times of 1 s, 2 s and 3.2 s and normalized thereafter, Figure 12.

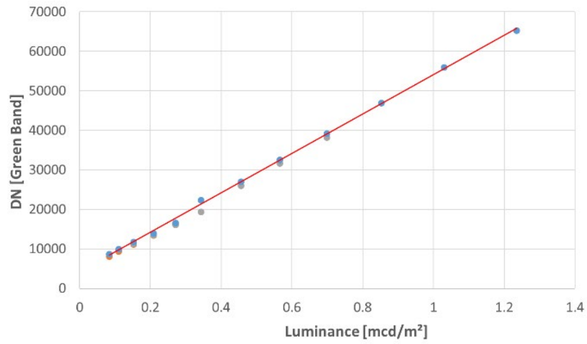

Figure 12. Exposure time normalized calibration curve of the M3E wide angle camera against the calibrated light source, only the cases when the green channel is not saturated are shown.

However, the magnitude of the determined luminance values did not match the expected values. For this reason, the power meter was replaced by the SQM-L in a further experiment. The relationship between the luminance derived from the calibration and the SQM-readings, transformed into luminance according to formula 1 is shown in Figure 13. Ideally, the luminance values would be approximately the same regardless of the method. In this case, the luminance values determined via the lab calibration are by a factor of 454 times lower than the directly measured values with the SQM.

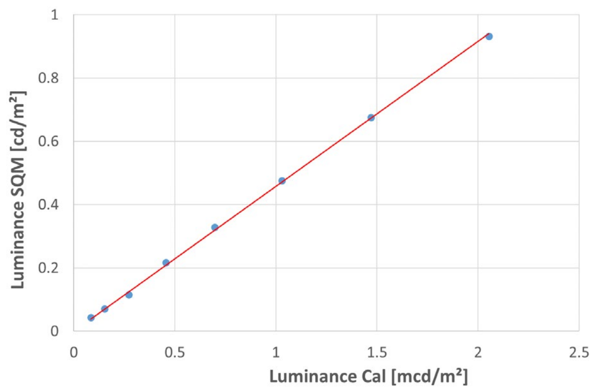

Figure 13. Correlation between SQM luminance values and the determined luminance during the radiometric calibration with the powermeter

3.1 Radiometric calibration vs. LCP- Method

When applying the determined calibration functions to the orthomosaics of flight 1 and 2, the grey values in the green band are between 1671 and 65,535 for the first flight and between 3243 and 65,535 for the second flight. The upper value of 65,535 means that the sensor has reached saturation and the light sources are therefore outside the measurement range of the recording. The two minimum values represent the dark noise. Dividing these values by the exposure time results in a value of around 1013 1/s for the first flight and around 1392 1/s for the second flight.

Both values are considerably smaller than the intercept of 2259.70 1/s determined during calibration (figure 12), which can be attributed to the lower temperature during the drone flights compared to the calibration measurements in the laboratory.

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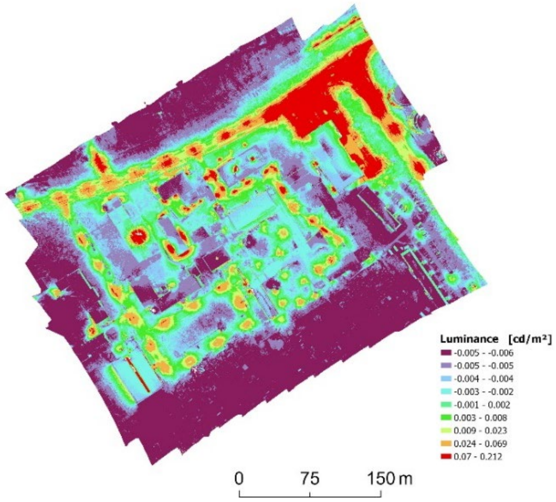

Figure 14. Night time luminance map based on drone flight of the campus area AUF on 2/28/2024 (20:20 - 20:32) based on the radiometric calibration approach

In order to be able to compare the luminance values determined with the SQM measurements on the ground, the regressions described above were used, Figure 14. As expected, the classified image, which was converted into luminance using the radiometric calibration, looks very similar to the orthomosaic calibrated using the LCP's.

However, the calculated luminance values differ quite significantly to the LCP-method. To determine the difference, 200 random points with various brightness levels were selected and compared, Figure 15.

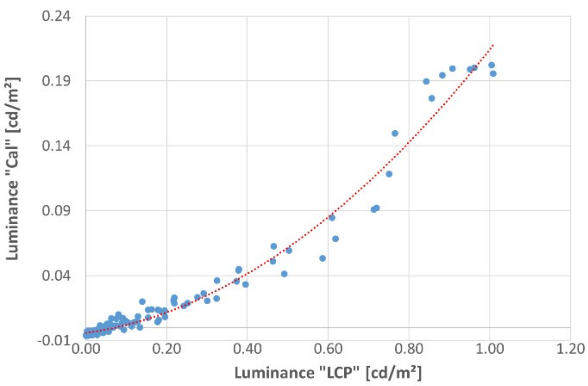

Figure 15. Comparison of the determined luminance with the radiometric calibration approach and the LCP-method based on 200 random points

The graph shows that the luminance calculated using the radiometric calibration is about a factor of 6 smaller and does not correspond linearly to the values of the LCP method. There are several possible reasons for the large deviation of the determined values from the LCP-method, which require further investigations. For example, when the camera was calibrated, only part of the image was illuminated with the defined luminance, while the rest of the image remained dark. This can lead to internal corrections not documented in the EXIF data being applied. Furthermore, the possible influence of different gain settings was not determined, which can cause problems (Fiorentin et al. 2020).

4. Conclusions

Commercially available RTK-GNSS drones, are able to quantify night-time light pollution with the help of LCP's. Long exposure times requires hovering for every exposure. Therefore, drones are best suited to cover small areas, i.e. a few hectares. Nevertheless, the presented methodology is well suited to determine the evenness of luminance in urban environments, soccer stadiums, etc. Cameras with time delay integration (TDI) could possibly allow for continuous imaging in the future.

Fully radiometric calibration of a commercial drone camera is a difficult task, because not all of the camera settings are provided as meta data to the user. Preliminary results showed a complex behaviour of the camera, which requires further investigations. Future work will also focus on image quality and the influence of exposure time and image brightness.

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