All Sky View
Monitoring of Diffuse Sky Brightness at Night

english version
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Contents

Cover Image

The cover image is an all-sky shot taken with the camera Sony alpha 6000 and a 190° fisheye lens by Meike (6.5 mm f/2.0) on 14.08.2017 at 23:28 CEST. The exposure time was 25 s at ISO 3200. The image shows the clear Starry sky, in which you can clearly see the Milky Way. Taken on the Schachen near Münsingen (southern Germany). The sky of this region is considered to be relatively dark. The sky is illuminated by surrounding artificial light. Nevertheless, on the horizon the light bells of the distant cities can be seen as brightening. The light on the upper right comes from the cities Reutlingen and Stuttgart, which are about 25 and 50 km away, respectively. and Stuttgart. On the lower right the light of the cities Albstadt and Balingen, which are approx. 40 km away, can be seen. The brightening of the left horizon was caused by the rising moon. In the same direction also lies the city Ulm.

Abstract

In Baden-Württemberg, the new Nature Conservation Act of July 2020 for the strengthening of biodiversity, the impact of artificial lighting on insect fauna is now also the focus of discussion.[1]. In § 21, specific regulations regarding lighting installations are outlined. The federal government's action program "Insektenschutz" of 2018, lists the reduction of light pollution as a measure for the protection of insects for the first time[2].

In this paper, the sky brightness and its progression over one night up to three years is documented. The brightness at the zenith is a standard used worldwide to measure the extent of light pollution. For this purpose, three camera stations have been developed, which at any time automatically take all-sky images of the sky and evaluate the nighttime images with focus on the sky brightness. After the cameras, which are commercially available system cameras, have been calibrated with a so-called Sky-Quality-Meter, the sky brightness can be calculated from the images. The camera in Dotternhausen, a small town with industry, has been in operation for more than three years. In August 2018, a second station was installed on the Schachen in the Swabian Alb biosphere region, an area considered to have little light pollution. A third station followed in September 2020 in downtown Heilbronn. The current images of the stations can be found at www.allskyview.de.

Compared to a purely natural sky, the sky above Schachen is brighter by at least a factor of 1.1, the sky above Dotternhausen by a factor of 2.1. The sky above the city of Heilbronn is brighter by at least a factor of 13.8 than it would be naturally, and by an additional factor of 16 if it is cloudy. If it is cloudy, the sky above Dotternhausen can be brighter by an additional factor of 10. Compared to Schachen, the sky can be brightened there by an additional factor of 2.3 due to evening cloud cover. In addition, the influence of natural light sources such as the moon and the Milky Way is higher on the Schachen than in Dotternhausen and almost no longer measurable in Heilbronn. Especially in Heilbronn, but also in Dotternhausen, artificial sky illumination by street and industrial lightings dominates over natural sources of brightness. A rate of change of sky brightness of typically 0.1 mag/arcsec^2 per hour was measured at the sites in the first half of the night. In the long term, the data from the camera stations will be used to quantitatively verify the effects of the Biodiversity Enhancement Act on light pollution. For this purpose, the "Landesanstalt für Umwelt Baden-Württemberg" (LUBW) was contacted.

[1] *Naturschutzgesetz Baden-Württemberg.* Gesetz. §21. July 23, 2020.

[2] Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit. *Aktionsprogramm Insektenschutz.* https://www.bmu.de/publikation/aktionsprogramm-insektenschutz/. Broschüre. Sept. 1, 2019.

1 Motivation of the Research

With the amendment of the Nature Conservation Act on 31.07.2020 to strengthen biodiversity in Baden-Württemberg, triggered by the initiative of the petition for a referendum "Artenschutz proBiene", the influence of artificial lighting is now also coming into focus, in addition to the influences of agriculture and climate change[3]. In § 21, it is pointed out, to avoid interference with insect fauna by artificial light in outdoor areas and to take into account above all the negative influences on insect fauna in the case of lighting installations. In addition, according to the new law, in the period from April 1 to September 30, it is forbidden to "illuminate the facades of structural facilities of public authorities, unless this is necessary for reasons of public safety or is prescribed by or on the basis of legal regulations." Since 2021, "newly constructed lighting installations on public roads, paths and squares [...] must be equipped with insect-friendly lighting that complies with the generally accepted rules of technology [...]" . The federal government's 2018 "Insect Protection" action program also identifies the reduction of Light pollution as a measure for the protection of insects is also listed[4].
So-called light pollution or light smog has a particularly negative effect on insects, birds, flying foxes, bats and other nocturnal animals. Artificial lighting causes insects to become disoriented and acts as insect traps, as the animals burn themselves on the hot surfaces of the lamps or become disoriented and swarm around the lamp, dying of exhaustion. For example, the decline in flying insect biomass by more than 75 percent over the past 27 years is due in part to increased artificial lighting[5]. But flora is also affected: Light pollution threatens the pollination of plants by nocturnal insects because they are affected by artificial light. Flowers under artificial lighting are visited around two-thirds less frequently by insects that pollinate them than flowers located in darkness. As a result, the plants' seed formation and thus their reproduction is reduced[6]. Also affected are migratory birds, two-thirds of which fly at night. During their flight, they orient themselves to the starry sky. When visibility is clear, they fly relatively high and are hardly affected by artificial light. In poor visibility, however, the birds stop their flight and seek sheltered places on the ground. In the process, they are attracted to artificial light and collide with glass facades or fly around until they are exhausted[7]. In general, artificial light sources have a negative impact on the natural circadian rhythm. Due to the powerful street lamps, which produce light of more than 100 Lux and are thus almost as intense as sunrise and sunset for living creatures, the light phases are prolonged. This has a negative impact on the resting and activity phases as well as on the timing patterns of reproductive and feeding behavior in animals[8]. In addition to animals and plants, humans are also affected by the brightening of the night by artificial light. Health problems can arise for people as a result of artificial light sources. The authoritative day-night rhythm, which clocks daily life, is impaired. For example, the rest hormone melatonin is only produced in darkness, which means that many people can no longer get their nightly rest due to artificial lighting. Furthermore, too much artificial light leads to sleep disturbances, stress and aggressiveness, an increased risk of cancer and heart attacks, as well as mental illnesses[9].

In Central Europe, the most significant factor in night sky brightness is man-made artificial light, which significantly illuminates the night sky. In this process, the light in the atmosphere is scattered by the air particles. On a clear night, the full moon increases the illuminance on the ground by a factor of 1000, strong street lighting even by a factor of 100,000[10]. In recent years, this light smog continues to increase, which is why light pollution is increasingly becoming the focus of research. Thus, both the intensity of artificial illumination and the extent of the illuminated area increased by about 2 % per year worldwide since 2012[11]. The 2016 Light Pollution Atlas also shows that more than 99 % of Europe's population lives

[3] *Naturschutzgesetz Baden-Württemberg*, see n. 1.
[4] Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit, see n. 2.
[5] M. Grubisic et al. "Insect declines and agroecosystems: does light pollution matter?" In: *Annals of Applied Biology* 173.2 (June 11, 2018), p. 180.
[6] E. Knop et al. "Artificial light at night as a new threat to pollination". In: *Nature* 548 (2017), pp. 206–209.
[7] L. D. Schuler. "Dark-Sky Switzerland für einleuchtende Dunkelheit". In: *Vierteljahrsschrift der Naturforschenden Gesellschaft Zürich* 158(1/2) (2013), pp. 1–10.
[8] M. Ebel et al. *Ökologie*. Braunschweig, 2013.
[9] *Folgen der zunehmenden Lichtverschmutzung*. Jan. 9, 2021. URL: https://www.sternenpark-schwaebische-alb.de/lichtverschmutzung/mensch-und-natur.html.
[10] Ebel et al., see n. 8.
[11] C. C. M. Kyba et al. "Artificially lit surface of Earth at night increasing in radiance and extent". In: *Science Advances* 3.11 (Nov. 22, 2017).

under light-polluted skies and 60 % can no longer see the Milky Way in the night sky[12]. The brightening of the night sky increasingly complicates astronomical research as well.
For the measurement and documentation of the sky brightness there are already some stations in Germany. Often sensors like a Sky-Quality-Meter measure the brightness of the sky. s The observatory Sankt Andreasberg, for example, carried out comparative measurements from 2010 to 2014 at two locations, which are about 15 km apart as the crow flies. The sky brightness was measured in Lux with sensors in one measuring station and then compared with the values of the other location in a diagram[13]. In this paper, the sky brightness is also documented over up to three years at three different locations in Baden-Württemberg. For this purpose, self-developed camera stations record all-sky images at intervals at any time. From the median 16 bit count values in comparison to the SQM values measured in parallel, a function can then be set up for each camera setting, with which the sky brightness can be calculated from the camera count values. Thus, the brightness needs to be recorded only once with the SQM to determine the relationship between sky brightness and camera count values. The SQM is particularly unsuitable for long-term measurement, since long-term darkening of the sensor protection glass due to UV radiation or heat effects of the sun has been observed. The measurement of the sky brightness based on the camera images has the advantage that an all-sky image is also available for the brightness values. This makes it possible, for example, to detect a switch-off of illuminations due to the changing brightness values and to prove this on the parallel all-sky images. Thus, other influences on the brightness of the night sky can also be determined, including clouds and airglow. In general, the time-dependent course of the sky brightness can be shown, e.g. during one night. This time dependence is not examined in the 2016 World Atlas of Light Pollution. Another advantage is the long-term investigation, which is made possible by the stations. Thus, long-term changes in sky brightness can also be detected. Thus, with the brightness values from the stations, the implementation of the Nature Conservation Act in Baden-Württemberg can be checked quantitatively.

There are also other uses for the camera stations:

- Stereoscopy and thus spatial measurement of meteors, airglow, satellites, high clouds, Northern Lights, etc.
- Weather camera
- Tourism interests
- Analysis of colors of the sky
- Transmission in planetariums, dome projection
- Monitoring bright stars

[12]F. Falchi et al. "The new world atlas of artificial night sky brightness". In: *Science Advances* 2.6 (June 10, 2016).
[13]M. Koch. *Vergleichende Messung der Himmelshelligkeit in Herzberg am Harz und St. Andreasberg.* Jan. 9, 2021. URL: http://www.astro-electronic.de/lightmeter.htm.

2 Technology

The Sony alpha 6300 camera is used in the camera stations, as it can also work without a mechanical shutter. It is controlled via two redundant single-board computers (BananaPI, Odroid, RaspberryPi). The operating systems Ubuntu Mate and Rasbian are used on these. The computers are connected with eight relays and can thus control the ventilation, camera connection, dome and lid heating as well as the power supply of the camera, computer and overall station. The two computers are also a mutual backup and can distribute or take over tasks from each other. The stations take pictures 24 hours a day. During the day, pictures are only taken at five-minute intervals with automatic exposure and sensitivity. At night, only the settings determined by the computer, for which the camera has been calibrated, are selected. The exposure time is always 25 seconds. Recorded images are directly checked for brightness and clouds by a script. If the sky is too bright or too dark, the sensitivity is adjusted for the next image. The camera station in Dotternhausen continues to run on the roof of a house. In August 2018, another station was added on the Schachen near Münsingen in Baden-Württemberg. This location is in the Schwäbische Alb biosphere area and is considered a comparatively dark region in Germany. At the beginning, the images taken were still processed in the respective station. For this purpose, there was a local 10 TB hard drive next to the two single-board computers. The analysis of the images was carried out by the stations themselves. However, as this computing power was not sufficient for flexible evaluation methods or was too slow, the data storage and analysis was placed on a separate server. This server was set up in Dotternhausen because there is a fast internet connection and the electricity can be obtained cheaply from a photovoltaic system. Debian 11 is installed as the operating system based on GUI and Linux. A total of 70 TB of hard disks are installed in the server and organised as Raid0. A Raid1 or Raid5 configuration was not used, as there is not enough memory available for backups with correspondingly large amounts of data. A script was implemented on the camera stations that intelligently transfers the recorded images to the server in order to continue to guarantee a live evaluation. During the transfer, the latest data is prioritised, compressed and transmitted accordingly. The server automatically picks up newly arrived images and begins to evaluate them. The measuring area is a round section in the zenith and comprises 520 pixels in diameter. This corresponds to the measuring range of the SQM used for calibration, which measures in a cone with a half-width of sensitivity (FWHM) of 20°. The median section is calculated from 16 bit count values of the measuring field. The following are recorded and calculated for each image: time stamp, ISO value, white balance, exposure time, median count values of the measuring field for red, green and blue, calculated count value according to the present calibration, calculated brightness of the sky, weather (cloudy or clear), possible errors during processing, the current moon phase, the height of the moon and the sun, the distance between the earth and the moon and the relative path to the storage location of the image. This data is stored in a MySQL database on the server. If contact with the outside is broken, the stations follow a specific programme sequence. In the process, the systems are restarted to ensure that the images can continue to be taken. So far, a total of over 1,000,000 data sets have been calculated.

FIG. 1: *Station at the experimenta in Heilbronn*

In September 2020, the third camera station was installed on the roof of experimenta in Heilbronn was installed. Due to the operation of the other stations over three years, technical and software problems repeatedly became apparent. Therefore, it was necessary to develop appropriate solutions during the planning and construction of the new station for Heilbronn. It was clear that the previous software was inflexible and difficult to operate. Some of these improvements are explained below. For example, all settings can now be specified in a JSON file, which the system then applies. The station's communication with the main server in Dotternhausen has been significantly expanded. The stations automatically establish a reverse SSH tunnel to the server. This also makes it possible to communicate with a station from the mobile network or behind a firewall. Such a tunnel is also used for a MYSQL master-slave synchronisation of the databases. In this way, all the station's data reaches the main server in real time and smooth operation in the event of network failures can still be guaranteed. Meanwhile, all data records of the database can also be searched interactively on a website. For this purpose, the cross-platform open source application "Grafana" is used, which is operated on the main server. Users can follow all station data live on a website or export and download specific data: https://allskyview.nsupdate.info/. Access to old image data is still pending. When this work is finished, the Grafana page will be linked to the previous website allskyview.de. In the meantime, the brightness curves and time lapses of the individual nights can be viewed there.

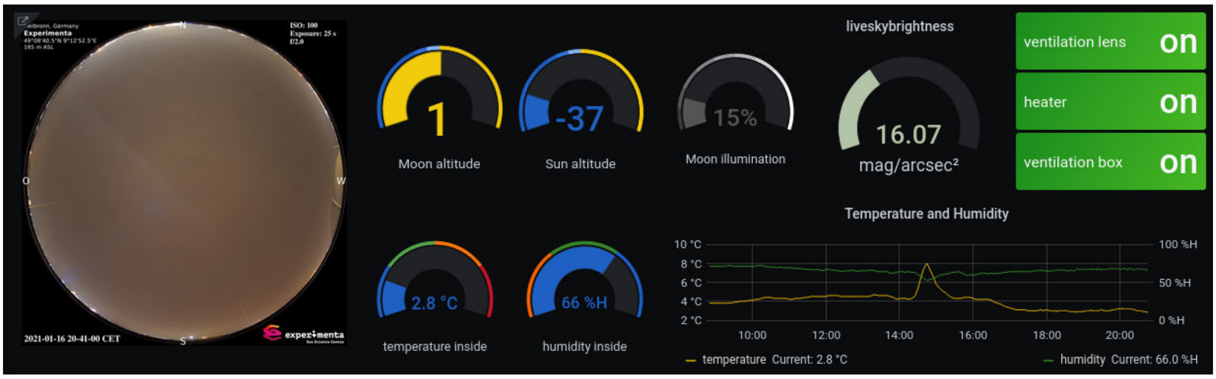

Fig. 2: *Screenshot of the live data display for the Heilbronn camera station*

Another disadvantage of the stations was the costly and time-consuming replacement of the acrylic glass dome in case of scratches. In addition, the dome fogged up on many nights despite the installed dome heating. To prevent this, a mounting ring for the dome and heater was designed and produced with the 3D printer. A ventilation system was integrated into the ring, through which a radial fan blows air past the heating wire directly into the dome. Lock nuts, which were printed into the ring, now make it possible to easily replace the dome from above by loosening six screws. This also makes it easier to protect the station from water penetration with a sealing ring. The ring itself is only 8 mm thick and thus saves space between camera, lens and aperture control. With the camera, it is important that it can be returned to exactly the same position even after maintenance work or disassembly, so that the data remain comparable and there are no shifts in the image. This is now made possible by a mount made of grooved aluminium profiles. The stepper motor with the aperture control is also mounted using this method. In order to be able to adjust the station exactly to the zenith, the station stands on a three-legged aluminium frame with adjustable threaded feet. To the left and right of the station is a shelf for weights that weigh the station down. This means that no anchoring has to be screwed or drilled when mounting on a roof. These improvements are to be gradually implemented for the stations in Dotternausen and Schachen as well.
At the station on the Schachen, an uninterruptible power supply was installed in spring 2020 so that this station can also record promising data, especially in the event of a power failure. In the event of a more widespread power failure, it would be possible to quantify directly the influence of the failed lighting on light pollution.

3 Brightness Calibration

3.1 Magnitude-Scale

Sky brightnesses are measured in the logarithmic magnitude scale, because this is close to the subjective brightness impression of the human eye. A change of the sky brightness by five magnitudes means a change by a factor of 100 of the light flux. Since the scaling of the magnitudes is logarithmic, a change of one magnitude has an increase or decrease of the light flux by a factor of $\sqrt[5]{100} \approx 2,512$ as a consequence[14]. The unit of the Sky-Quality-Meter (mag/arcsec^2) is therefore suitable for the scientifically comparable brightness measurement of the cameras. With the following formula, the difference between two brightness values m_1 and m_2 can be used to determine by which factor f the sky is brighter or darker.

$$f = 10^{\frac{m_1 - m_2}{2,5}}$$

3.2 Calibration

In order to convert the camera's counts to mag/arcsec^2, calibration measurements taken over several nights at different weather conditions are needed. These must also be made for each ISO sensitivity of the camera. With brightness values, which were measured with moonlight, it was noticed that the values of the SQM were systematically too bright. Although the moon was not high enough to be directly in the SQM's measurement field in the sky, moonlight from the side glared into the SQM, increasing the measured brightness value – while the camera station correctly calculated the actual sky brightness. The higher the moon was in the sky, the more it glared into the SQM, increasing the difference between the SQM value and the calculated brightness. This influence of lateral incidence of moonlight into the SQM could be confirmed by hand experiment. A full moon brightens the indication of the SQM by nearly 0.4 mag, although it lies far outside the indicated half width of the measuring field of the SQM. Therefore value pairs, with which the moon stood at least 20° over the horizon, were sorted out for the further calibration. This limit was determined by own empirical values. Afterwards for each ISO setting and location values were removed, which were far in the brightness range of another ISO setting. In addition, obvious measurement errors were removed.

The SQM, with which the sky brightnesses were measured, was calibrated with two other SQMs among themselves. Thus, the sky brightnesses were measured in one night with three SQMs in parallel at the same location and finally an average value was formed from the three measured values. Based on the average deviation of the SQM from the mean value, a correction value was determined for each SQM. For the SQM used here, the correction value was +0.06 mag/arcsec^2. This value was added to the measured sky brightnesses before the brightness calibration of the stations.

[14] A. Unsöld and B. Baschek. *Der neue Kosmos.* Berlin and Heidelberg: Springer-Verlag, 1988, p. 129.

If the count values of the red, green and blue channels for the ISO setting 1600 against the corrected brightnesses of the SQM are plotted, the following diagram is obtained. (Fig. 3). Overexposed count values >45,000 were sorted out. This limit was set after looking at the images with high count values. It can be seen that the colors of the clear sky, i.e. at large SQM values, are always the same, resulting in a uniform curve for each color channel. Indeed, brightness values >20 mag/arcsec^2 are reached only in clear sky.

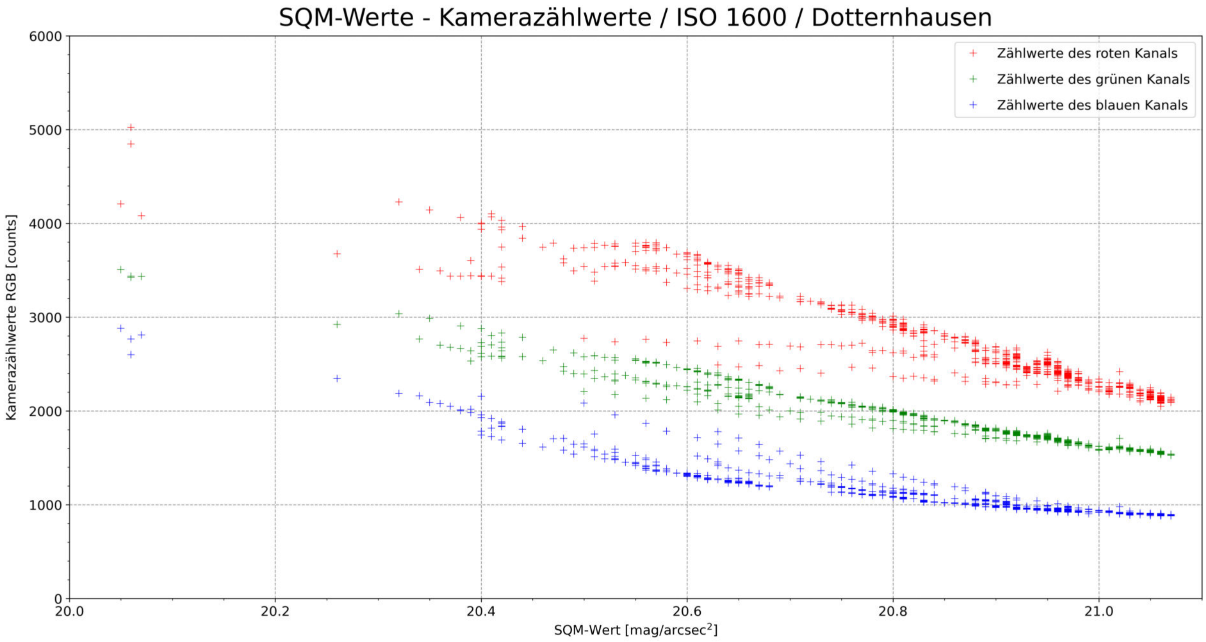

FIG. 3: *SQM values versus camera counts for ISO 1600 in Dotternhausen*

The SQM measures visual brightness through a cyan-colored filter. Therefore, the count values of the red channel were not considered for further calibration. A factor was now sought for each of the blue and green channels so that the sum of the two channels yields a curve that is as common as possible. Systematic approximation yields the factor 0.57 for the green and correspondingly $1 - 0.57 = 0.43$ for the blue count values. Thus, after adding the two factorized values, the narrowest common curve of green and blue is obtained. In the next step, the weighted total k of green $\cdot$ 0.57 and blue $\cdot$ 0.43 is logarithmized to base ten to check if the graph can be modeled with a linear function.

Linear regression can now be used to determine a linear function equation of the form $y = m \cdot x + b$ (y = logarithmized camera count value from green $\cdot$ 0.57 + blue $\cdot$ 0.43; x = measured SQM value [mag/arcsec^2]), which can be used to describe the relationship between logarithmized camera counts and the SQM values. After these steps have been performed for each ISO setting, these regression lines can be plotted for the calculation of the brightness value in mag/arcsec^2 from the weighted total k value (Fig. 4).

For the stations in Dotternhausen and on the Schachen especially the ISO setting 1600 is interesting. Dark luminosities > 20 mag/arcsec^2, as they are reached at the two locations, are almost exclusively recorded with ISO 1600. The readings for this ISO setting lie relatively well on a straight line and have a relatively small deviation from the regression line. In addition, most of the calibration data is also available for this ISO value. In Heilbronn, brightness values dimmer than 19.15 mag/arcsec^2 were not measured in this paper. Therefore the station was calibrated only for the ISO settings 100, 200, 400 and 800.

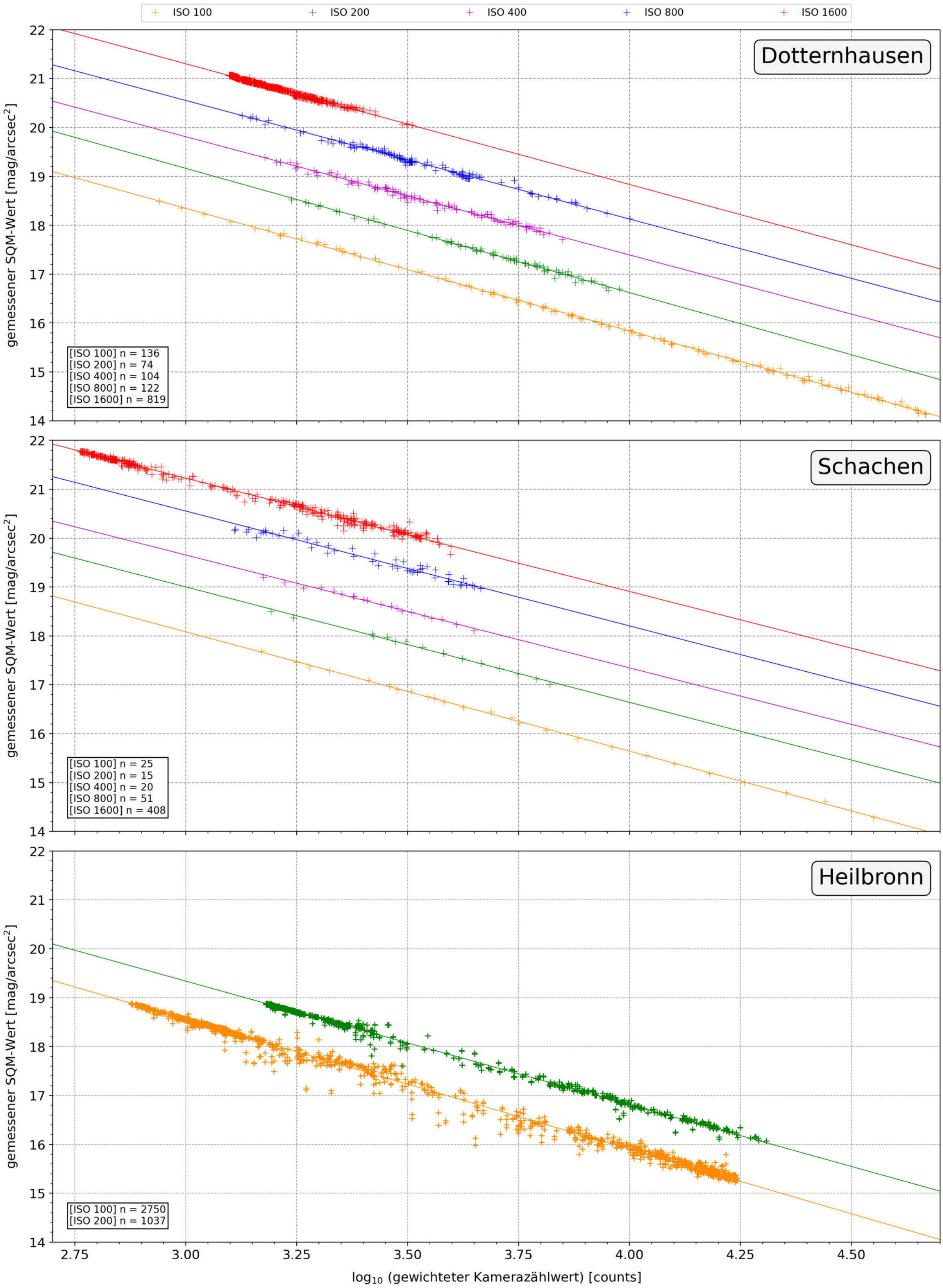

FIG. 4: *Calibration overview for each site*

3.3 Error Estimation

As can be seen in Fig. 4, the data points have some deviation from the regression line. A standard deviation σ was calculated for each ISO setting and for each site (Tab. 1). Since the standard deviations are too small to visibly display for each data point in the following brightness plots, they are listed in Tab. 1 and apply to all indicated brightness values calculated by the stations.

TAB. 1: *Standard deviation from the respective regression line in [mag/arcsec^2].*

Standort	ISO				
	100	200	400	800	1600
Dotternhausen	± 0,029	± 0,034	± 0,044	± 0,041	± 0,017
Schachen	± 0,024	± 0,032	± 0,031	± 0,079	± 0,049
Heilbronn	± 0,038	± 0,030			

3.4 Error Propagation

The standard deviation in Tab. 1 indicates the error due to the brightness calibration. Due to this standard deviation, further errors result from further calculations with these brightness values. These errors can be precisely quantified by error propagation. In the following, the error for the brightness factor f resulting from the standard deviations is calculated using the error propagation as an example. The brightness factor f indicates the ratio of two light fluxes at a given magnitude difference, i.e. in this case by how much the sky over one location is brighter than over the other (see p. 5). Assume a brightness difference $d = m_1 - m_2 = 0.8$ mag/arcsec^2 with standard deviations for ISO 1600 in Dotternhausen of $\Delta m_1 = 0.017$ mag/arcsec^2 and $\Delta m_2 = 0.049$ mag/arcsec^2.

Error for the brightness factor f:

$$\Delta f = \sqrt{\left(\frac{\partial f}{\partial m_1} \cdot \Delta m_1\right)^2 + \left(\frac{\partial f}{\partial m_2} \cdot \Delta m_2\right)^2}$$

$$\Delta f = \sqrt{\left(0,4 \cdot \ln(10) \cdot 10^{\frac{0,8}{2,5}} \cdot 0,017\right)^2 + \left(0,4 \cdot \ln(10) \cdot 10^{\frac{0,8}{2,5}} \cdot 0,049\right)^2}$$

$$\Delta f \approx 0,0943 \approx 0,09$$

The error for the brightness factor f is therefore ± 0.09. With a brightness difference of 0.8 mag/arcsec^2, the brightness factor can also be 2.09 + 0.09 = 2.18 or 2.09 - 0.09 = 2.00 due to the error in the calibration.

4 Brightness Gradients and Discussion

4.1 Course of Dotternhausen, Schachen and Heilbronn with their comparison

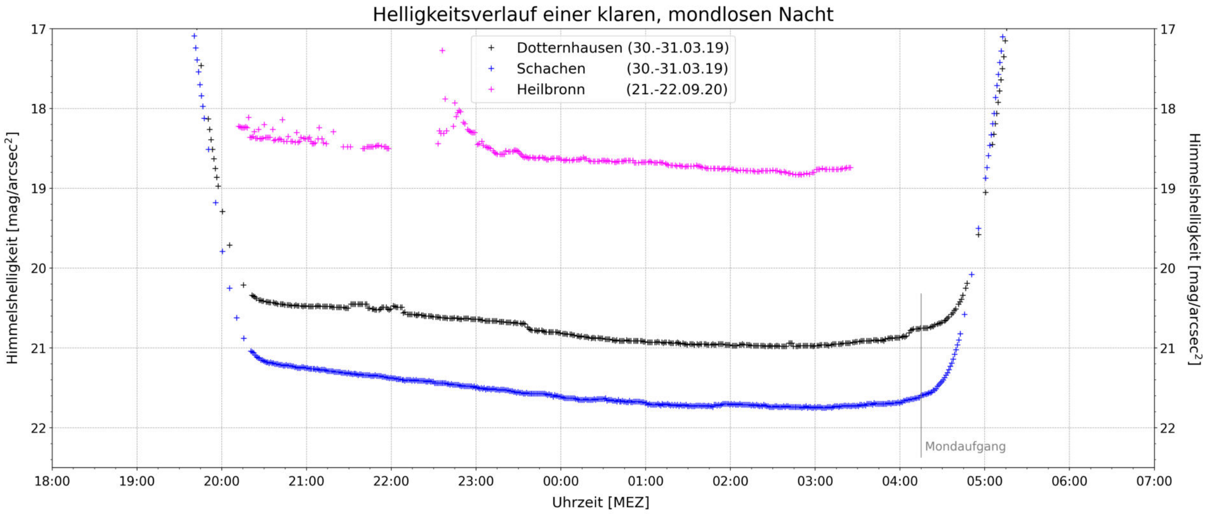

Fig. 5: *Typical brightness curve of a clear, moonless night. The conditions were similar at all three locations: date around the equinox, no moonlight and no clouds.*

The brightness curve in Heilbronn is from the first night of the camera station at experimenta. Since work was done at the station until midnight and clouds were still passing by, some brightness values break out in the first half. After dusk, the brightness decreases by an average of 0.09 mag/arcsec^2 per hour until 2:45 am. It reaches its minimum there at 18.83 mag/arcsec^2. After dusk, the sky was 1.7 times brighter than at minimum. In the course of the night, some, often small, steps can be seen. In the images, for example, the switching off of a bluish emitter and a bundled beam of light can be seen.

In Dotternhausen, the sky brightness also decreases with an hourly rate of change of 0.1 mag/arcsec^2 after the end of dusk until 2:30 am. There it reaches the minimum of 21 mag/arcsec^2. At this time, the sky is 1.6 times brighter than shortly after dawn. Especially in the first half of the night, several steps and jumps can be seen. These are caused, for example, by switching on or off floodlights or yard lights as well as by dimming the street lights, as can be seen in the camera images. From 3 o'clock onwards, the brightness increases again due to moonrise and later due to sunrise.

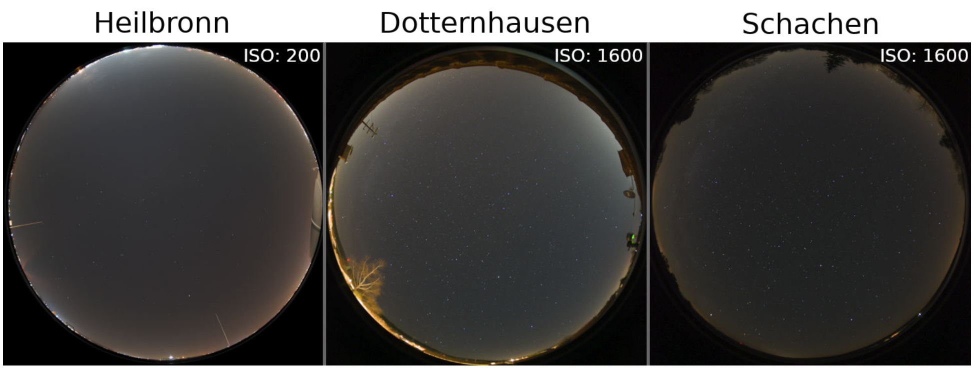

Fig. 6: *Images of the three camera stations at the darkest time of the respective night. Please note: Dotternhausen and Schachen have the same sensitivity, Heilbronn would be roughly eight times brighter at this sensitivity.*

After dusk, the sky brightness on the Schachen decreases uniformly with an average rate of change of

0.10 mag/arcsec^2 per hour until 1:30 am. No steps or jumps can be seen in this interval which can be directly attributed to switching off of illuminations. This is probably due to the fact that there are only few illuminations in the direct vicinity of the Schachen and the artificial light comes much more from the light bells of the more distant cities such as Münsingen, Reutlingen, Stuttgart and Ulm. Between 1:30 – 3:15 the sky brightness was lowest at about 21.75 mag/arcsec^2. So after twilight the sky was 1.6 times brighter than at the darkest time. From 03:15 the sky brightness increases again due to the rising moon.

In the period 9:00 pm to 1:30 am there is a change of 0.47 mag/arcsec^2 in Dotternhausen and on Schachen, while the brightness in Heilbronn changes by 0.34 mag/arcsec^2. In Heilbronn this corresponds to an hourly rate of change of 0.08 mag/arcsec^2, in the other two locations to a change of 0.10 mag/arcsec^2 per hour. At 9pm the difference between Heilbronn and Schachen is 2.87 mag/arcsec^2, at 1:30am even 3.01 mag/arcsec^2. This means that the Heilbronn sky is about 14 times brighter than the one over the Schachen after dusk, and even 16 times brighter in the middle of the night. So the difference between the two places increases during the night. This also applies to the difference between Dotternhausen and Heilbronn. At the darkest point in the night, the sky above the large city of Heilbronn is brighter by a factor of 15 than the sky above the rural Schachen at the minimum in the spring night. Compared to the small town of Dotternhausen, the sky over Heilbronn is seven times brighter. The three locations also differ in the timing of the minimum of a night. On Schachen, the nightly minimum cannot be fixed to a point in time. There is much more a period of about two hours during which the brightness does not change or changes only very slightly. In Dotternhausen and Heilbronn, on the other hand, the minimum sky brightness can be fixed fairly precisely to a point in time, in Heilbronn even more clearly. This may be related to the influence of artificial light, as this has an effect on brightness throughout the night in Dotternhausen and especially in Heilbronn. So the sky brightness in Heilbronn can never drop below about 19 mag/arcsec^2, in Dotternhausen never below about 21 mag/arcsec^2. At both locations, there is only one time during the night when the influence of artificial light is at its lowest, for example, because the street lighting is dimmed or switched off completely. However, the Schachen does not seem to be completely free of light pollution either, as there is also a decrease in brightness between the end of dusk and the beginning of the darkest phase - most likely due to a decrease in artificial light, as the natural brightness influences remain relatively constant during a night.

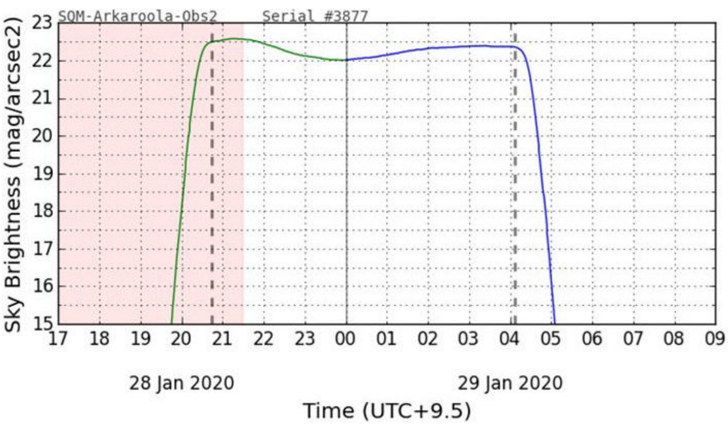

FIG. 7: *Brightness curve of Arkaroola, Australia. (Source: Andrew Cool)*

Andrew Cool also takes sky brightness measurements in Arkaroola, a nature reserve in the Australian outback about 800 km north of Adelaide[15]. There, the darkest point in time is reached approx. 30 min after the end of dusk (see Fig. 7). Thus, in contrast to the locations investigated in this paper, there is no prolonged, continuous decrease in brightness after dusk around 20:40 local time. Afterwards, the Milky Way wanders through the measurement field, resulting in a maximum brightening of about 0.6 mag/arcsec^2 at midnight.

[15] A. Cool. private Korrespondenz. 2018.

4.2 Influence of the moon on sky brightness

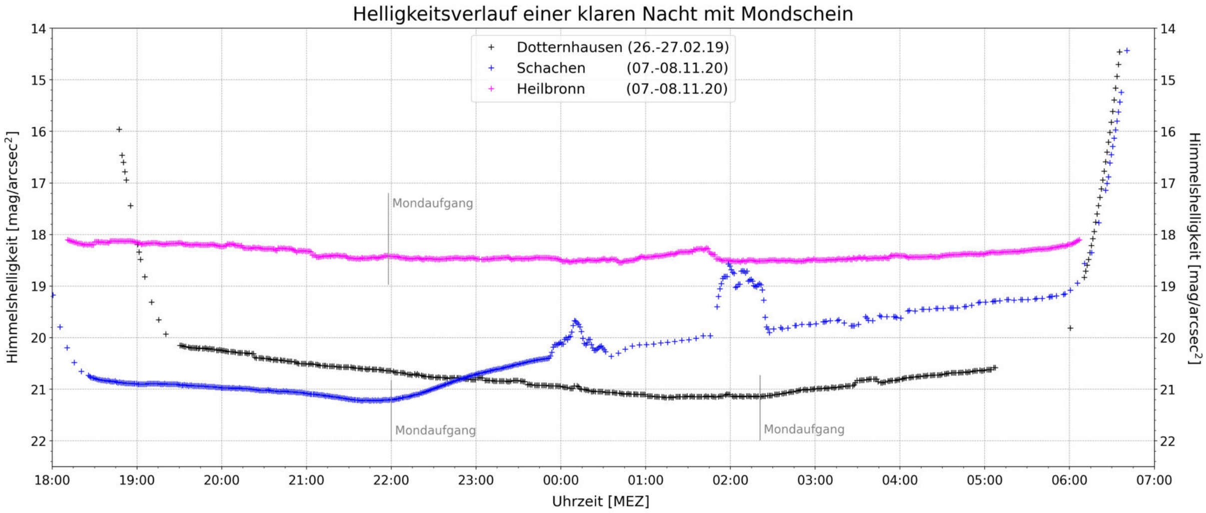

FIG. 8: *Course of sky brightness on a night with rising moon*

One hour before the rise of the crescent moon on the November night at 10 pm, the difference between Heilbronn and the Schachen is 2.76 mag/arcsec^2. As the moon then rises, the curve from the Schachen rises sharply, while the sky brightness over Heilbronn remains constant. Thus, one hour after moonrise, the difference in brightness is still 2.23 mag/arcsec^2. The brightness over the Schachen then continues to increase with increasing altitude of the moon. In Heilbronn, in contrast, the brightness remains unchanged with one exception between 1-2 o'clock due to cloud fields.

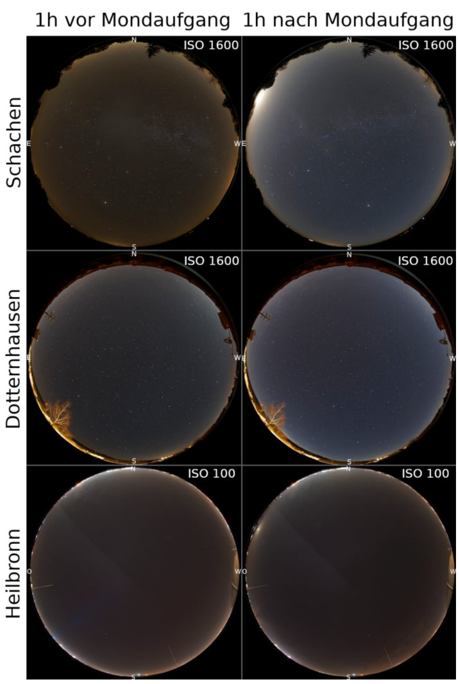

FIG. 9: *Recordings from the Camera stations one hour before and one hour after moonrise.*

In Dotternhausen, the rise of the crescent moon results in an increase in sky brightness. One hour before the rise the brightness is 21.14 mag/arcsec^2, one hour after 20.93 mag/arcsec^2. The difference between one hour before and after moonrise is 0.21 mag/arcsec^2 in Dotternhausen and 0.38 mag/arcsec^2 on the Schachen. The influence of the moonlight on the brightness is therefore greatest on the Schachen. In Dotternhausen this influence is lower, while in Heilbronn at least no brightening of the sky by the crescent moon could be measured. The darker the location, the higher the influence of the moonlight on the sky brightness seems to be.

This observation was confirmed by Wuchterl and Reithofer. In their 2017 paper "Licht über Wien V", they came to the conclusion that it hardly mattered for the brightness of the sky over Vienna whether the full moon was in the sky, as the brightening of the sky by artificial light was at "such a high level"[16]. The sky over Vienna is naturally brighter than the sky over Heilbronn, but a tendency can be discerned. In Heilbronn, a large city, the moon has a very small influence on the sky brightness due to the strong brightening of the sky by artificial light. In Dotternhausen, a small town with industry and commerce, the moon also has a smaller influence than on the Schachen, an area considered to be low in light pollution.

[16] G. Wuchterl and M. Reithofer. *Licht über Wien V - Entwicklung der künstlichen Nachthimmels-Aufhellung über Wien in den Jahren 2011 bis 2017.* Report. 2017.

4.3 Influence of clouds on sky brightness

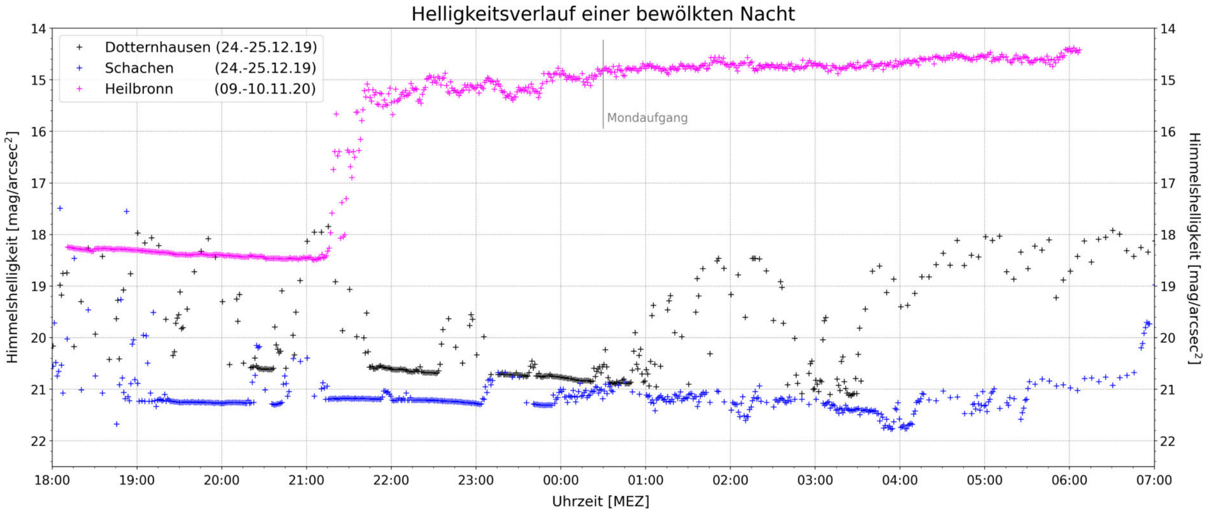

FIG. 10: *Course of sky brightness on a partly cloudy night*

The brightness curve for Schachen and Dotternhausen shows a moonless night alternating between clouds and clear skies. For Heilbronn, a night was selected which is continuously cloudy from about 9:30 p.m. and in which the moon rises after midnight. Strong fluctuations in brightness are common in cloudy skies under the influence of artificial light. Clouds scatter the upward scattered by clouds and thus increases the effect of light pollution.

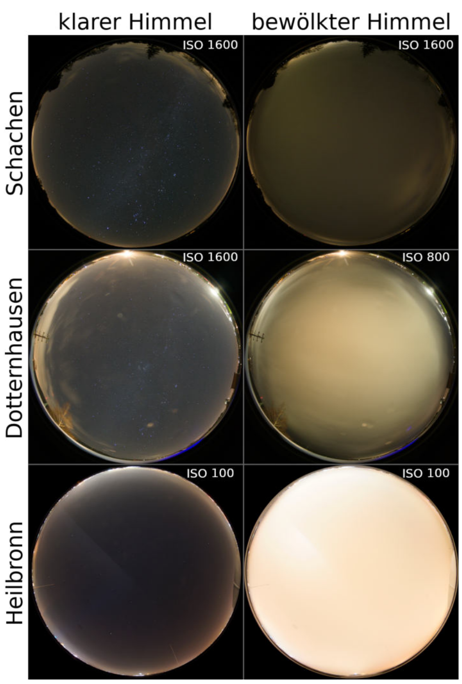

FIG. 11: *Shots from the three camera stations with cloudless zenith and overcast sky.*

In regions without artificial brightening, this effect is usually reversed, as the clouds obscure natural light sources. The brightness gradients shown here illustrate this. From about 1:00 a.m. onwards, the sky on Schachen. Nevertheless, brightness values similar to those of clear conditions were measured on Schachen. In Dotternhausen, the sky is about 2.5 mag/arcsec^2 brighter in cloudy conditions than in clear conditions, which corresponds to a factor of 10. Of course, the brightening effect of clouds is greatest in Heilbronn, the location with the most light pollution. There, cloud cover causes the sky to brighten by about 3 mag/arcsec^2, which corresponds to a factor of 16.

4.4 Seasonal course of the midnight brightness

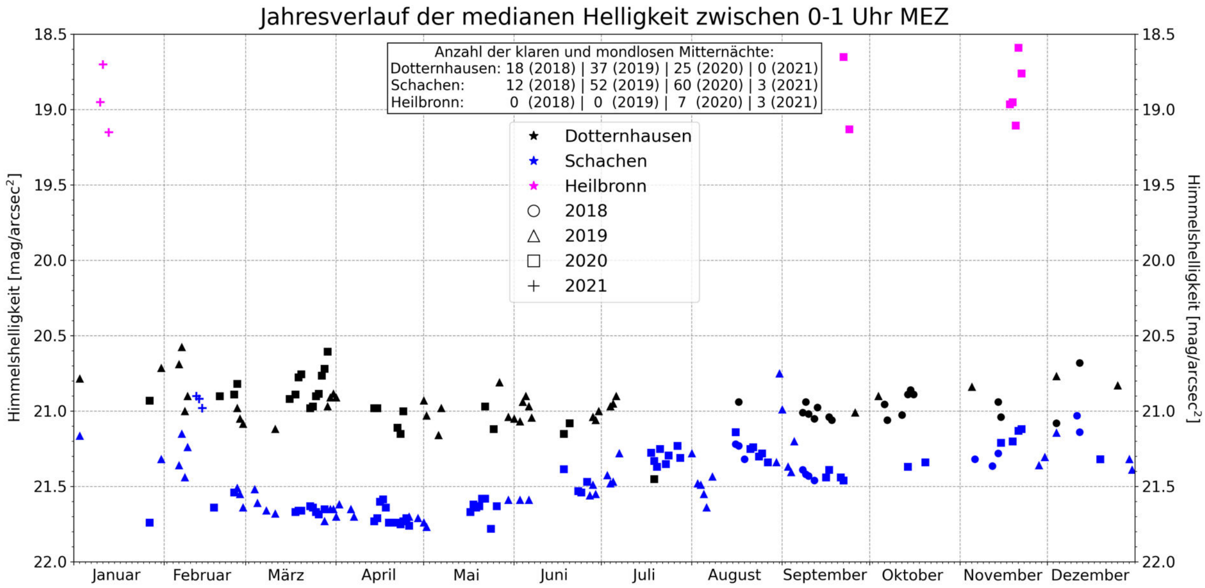

FIG. 12: *Course of the midnight brightness of both locations from January 2018 to February 2021 under the same sky conditions as far as possible (s. b.).*

The diagram shows the brightnesses at local midnight (approx. 00:30 CET) over the course of the year. Between 00:00 and 01:00 CET, as many images as possible were taken from this period that fulfilled the following selection criteria: clear sky in the measurement area, sun at least 18 degrees below the horizon, moon at least 12 degrees below the horizon and no briefly visible artificial light. For each night that met these conditions, the median average of the brightness values between 00:00 and 01:00 CET was calculated in order to minimise any remaining fluctuations. Due to technical problems, no data is available from the camera station in Dotternhausen for the second half of 2020.

The diagram clearly shows the systematic difference in brightness between the stations Schachen and Dotternhausen. At midnight, Dotternhausen is on average 0.6 mag/arcsec^2 brighter than Schachen. The systematic seasonal variation of the midnight brightness is due to the influence of the Milky Way. A bright part of the Milky Way is at its zenith between July and September. Only in January do the fainter regions of the Milky Way also disappear from the measurement range. In the months of February to May, the Milky Way is not in the sky or is lower in the sky. This can be seen in the course of the Schachen. Because the sky in Dotternhausen is 1.74 times brighter, the influence of the Milky Way cannot be seen there. There, artificial light sources dominate the brightness of the sky. The same is expected for Heilbronn during the year, as the sky there is roughly a factor of ten brighter than on the Schachen. Comparing the months of August, November and December with March to May, the influence of the Milky Way on sky brightness at the Schachen can be given as about 0.3 to 0.4 mag/arcsec^2. The short-term fluctuations in brightness can be explained mainly by varying weather conditions. Even with a clear sky, the visibility varies with the number of aerosols in the air. Hazy skies scatter a lot of artificial light and thus brighten the starry sky. Especially at the bright sites this leads to a larger scatter of data, while at the Schachen the data is quite consistent.

4.5 Long-term course of midnight brightness

A long-term trend in sky brightness over the recorded period cannot be discerned. If we look at the months of August and September in the Schachen and Dotternhausen over the three years, the brightness values lie on a common line. This means that the midnight brightness in late summer at both locations has not changed over the last three years.

5 Overall discussion and literature comparison

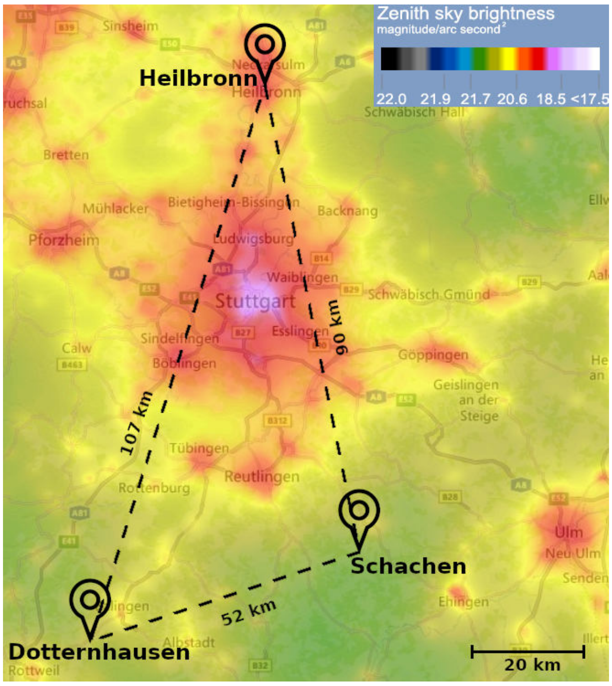

FIG. 13: *Extract from the 2015 World Atlas of Light Pollution by Falchi et al. (source: https://www.lightpollutionmap.info/).*

For Dotternhausen, a minimum sky brightness of 21.2 mag/arcsec^2 was measured, which corresponds to a factor of 2.1 compared to a natural sky. On the Schachen a minimum sky brightness of 21.85 mag/arcsec^2 was measured, which corresponds to a factor of 1.1 compared to a purely natural sky. The inner-city station in Heilbronn measured 19.15 mag/arcsec^2 as minimum brightness, which corresponds to a factor of 14. Falchi et al. give a brightness value of 21.28 mag/arcsec^2 for Dotternhausen, 21.51 mag/arcsec^2 for the Schachen and 19.69 mag/arcsec^2 for Heilbronn in the World Atlas of Light Pollution from 2015 (see Fig 13). For Dotternhausen, this value roughly corresponds to the one measured in this paper. For Schachen, up to 0.3 mag/arcsec^2 darker values were measured, in Heilbronn the values were at least 0.54 mag/arcsec^2 brighter. However, Falchi et al. did not investigate any temporal dependence. From January 2018 to February 2021, no long-term changes in light pollution are yet discernible (see Fig. 12).

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Measurements by Andrew Cool in the Australian outback Arkaroola show the typical sky brightness without any light pollution. Over the entire year 2018, brightness values of approx. 22 mag/arcsec^2 are most frequently reached there (s. Fig. 14). The more often a brightness value is reached, the brighter its colour in the diagram. This diagram proves the value of approx. 22 mag/arcsec^2 as the natural night sky brightness.In the immediate vicinity of the camera station in Dotternhausen there are some sources of artificial light (see Fig. 15).

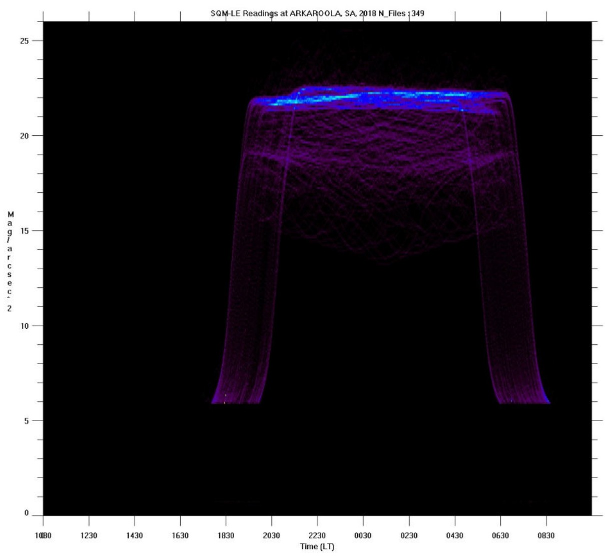

FIG. 14: *SQM measurements from 2018 in Arkaroola, Australia (Source: Andrew Cool)*

Especially in cloudy conditions, this leads to a brightening by a factor of 10 compared to a clear sky. Night-time photographs of the surroundings were taken in order to be able to precisely quantify the influence of some light sources. For this purpose, the images could be compared with the station's brightness values measured in parallel. For example, switching off the sports field floodlight in Erzingen, the brightest light source in the village, resulted in a darkening of the sky by 0.03 mag/arcsec^2. In general, the lighting cut-offs of municipalities, companies and private houses can be seen in the photographs. As described, this leads to a continuous decrease in sky brightness in the course of a night. Kyba et al. put the share of street lighting in the total visible light emissions of the city of Tucson in Arizona at 16-21%.[17].

FIG. 15: *Images from the 1000 m high Plettenberg near Dotternhausen in August 2018. The lower image was taken six hours later.*

Large cities like Heilbronn are almost decoupled from the cycle of natural light sources at night. With a sky that is at least 14 times brighter than the natural sky, the moon has a negligible influence on the brightness of the sky, and the Milky Way has no influence at all. But even on the seemingly remote Schachen, the sky is brighter by at least a factor of 1.1, at times even up to 2.3 when there is high evening cloud cover. Cities such as Stuttgart (distance approx. 50 km), Reutlingen (approx. 25 km) and Ulm (approx. 40 km) have an influence on the sky brightness above the Schachen despite their distance. Especially when clouds are high, their light is widely scattered. Local light sources such as the towns of Münsingen and Ehingen, the nearby village of Buttenhausen and an adjacent farm also brighten the night sky. Light pollution is therefore not only a problem of urban areas. It extends far into the rural regions.

However, there are ways to reduce the influence of artificial illuminations on sky brightness.[18]. The luminaires should be fully shielded and the light should only be directed where it is needed. Here it is important that the luminaires "do not emit light in and above the horizontal", as this is "scattered over long distances in the atmosphere". In terms of light colour, warm white, UV-free light with a colour temperature of less than 3000 Kelvin and correspondingly lower blue components is preferable. When modernising lighting, lamps with high efficiency should be used. Accordingly, the connected load should then be reduced in order to save energy with the same amount of light. In addition, the demand for lighting requirements, the duration of illumination and the amount of light should be carefully planned.

[17] C.C.M Kyba et al. "Direct measurement of the contribution of street lighting to satellite observations of nighttime light emissions from urban areas". In: *Lighting Research & Technology* 0.0 (Oct. 28, 2020).

[18] Fachgruppe DARK SKY der Vereinigung der Sternfreunde e.V. *Energiesparende und umweltgerechte Beleuchtung.* https://www.sternenpark-schwaebische-alb.de/downloads/printmedien.html. Aug. 2017.

6 Outlook

In the future, one aim of the camera stations will be to quantitatively check the effect of the Biodiversity Enhancement Act in BW on sky brightness. Contact has already been made with the Landesanstalt für Umwelt Baden-Württemberg (LUBW) with a view to possible cooperation. In this way, the LUBW can expand its network of measuring stations for environmental observation and evaluate the brightness measurements of the camera stations together with data from its other measuring networks. The evaluation procedures are to be further automated and the processed results will also be available to the public at www.allskyview.de. The publication of this paper as an Open Source project is also being planned.

The 360°x180° panoramas from the camera stations can be displayed rectified in virtual reality glasses and in a planetarium dome. This data, which has a resolution of up to 8K, can be visualised as an image and time-lapse combined with the measured brightness curves. The images and data can then be presented to the general public in experimenta's in-house planetarium. Special events such as the airglow or bright meteors can also be presented very realistically in this way.

A very interesting question is to what extent the found common rate of change of sky brightness from 0.10 mag/arcsec^2 to 0.14 mag/arcsec^2 per hour in the first half of the night is universal. The extent to which this is due to light pollution or natural influences will be investigated with further stations and analyses. The installation of a camera station in an environment without light pollution is also being considered, but unfortunately this is no longer possible throughout Germany, as can be seen in the light pollution atlas by Falchi et al.

In order to be able to carry out brightness measurements with parallel Allsky images flexibly and independently of the existing infrastructure, the construction of a mobile camera station is very interesting. A self-sufficient station can be set up at locations without power and internet supply for a few nights. This allows more brightness data to be collected with images at different locations without having to install a station each time at great expense.

With a powerful drone, for example, the light pollution at a location can be better measured spatially. A drone equipped with SQM and a camera can thus measure the surroundings of a camera station more precisely in terms of sky brightness, e.g. how the sky brightness changes with increasing flight altitude. The first measurement flights have already been made on the Schachen. Currently, the data is still being evaluated.

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All figures – unless otherwise indicated – are by Antonio Schmusch.