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## FUTURE LONG-TERM NIGHT SKY MONITORING PROJECTS SHALL USE MULTISPECTRAL IMAGING SENSORS WHEN POSSIBLE

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### Abstract

Interest in investigation of the impact of light pollution on ecology leads to a surge of observations and measurements. This article presents the measurement of the night sky radiance in over a period of 4.5 years in the city of Bremen, Germany from two sites situated in suburban and rural areas. It was found that both sites show a decreasing trend in sky radiance. However, since no multispectral images were taken, the exact cause of the decrease cannot be determined. It is therefore recommended that future night sky measurements should be based on multispectral imaging, for example by commercial digital cameras.

**Keywords:** *Sky Quality Meter, light pollution, night sky radiance*

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## AZ KÖVETKEZŐ ÉJSZAKAI ÉGBOLT FELMÉRÉSEK ALKALMÁVAL MULTISPEKTRÁLIS KÉPI MÉRÉSEKET KELL HASZNÁLNI

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### Összefoglalás

A fényszennyezés ökológiai hatásának vizsgálata iránti érdeklődés megfigyelések és mérések sokaságát indította el. Ebben a cikkben egy Bremenben (Németország) elvégzett 4,5 éves égboltradiancia-méréssorozat eredményeit közöljük. A mérések két helyszínen, egy külvárosi és egy vidéki területen történtek. Mindkét helyen csökkenő tendenciát találtunk az égbolt fényességében. Azonban nem történtek multispektrális mérések, a csökkenés pontos oka nem határozható meg. Ezért javasoljuk, hogy a jövőben tervezett fényszennyezés-felmérések esetében történjen multikulturális leképező radiometria, pl. digitális kamerák segítségével.

**Kulcsszavak:** égboltminőség-mérő, fényszennyezés, éjszakai égbolt radianciája

## Introduction

To assess the impact of technological and behavioral change in lighting and use of artificial light, it is necessary to monitor the night sky over a long period. This can be either achieved by satellite-based (e.g. with VIIRS-DNB sensors onboard the Suomi NPP and JPSS series of satellites) or ground-based measurements. The gradual change of lighting technology from HPS and compact florescent lighting to solid-state lighting, for example LEDs, provides an opportunity to identify the impact on skyglow by means of long-term measurements. However, most of the ground-based long-term measurements in the past were carried out on panchromatic sensor, most of which incapable of making spatially resolved measurements, for example using the inexpensive Sky Quality Meter (SQM) which is a popular panchromatic photodiode radiometer.

This article presents the results of a long-term measurement in Bremen, Germany using two SQMs previously shown in a dissertation (Tong (2016)), and demonstrates the reasons a panchromatic device without imaging capability hampers the ability to pinpoint the sources of both short-term and long-term changes.

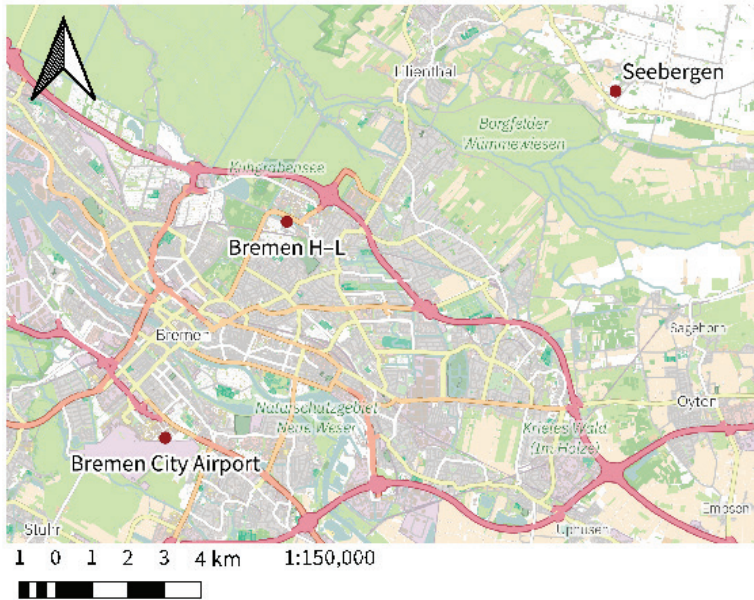
## Material and methods

### *Description of measurement sites*

The city of Bremen, situated in Northern Germany surrounded by the federal state of Lower Saxony, is the tenth largest city in terms of population and the fifth largest in terms of area. Built along the Weser River, Bremen is a typical European medium-sized city, with land uses ranging from heavy industries and logistics, to parks and natural reserves. Topographically Bremen is a flat city with an elevation of 10.5 m above mean sea level at the marketplace of the city center, and a maximum natural elevation of 32.5 m, the lowest among all states within Germany (Herbert 2009) (Fig. 1).

The public lighting system of Bremen consists mainly of a mixture of fluorescent lights for low-power, small-area uses, and high-pressure-sodium (HPS) lights when high output power is necessary. Since ca. 2013, new installations of public lighting systems involve the use of white LEDs of different models with various color temperatures, which cannot yet be quantified due to lack of appropriate instruments, such as a calibrated spectroradiometer.

The weather station of the source of weather data (Bremen City Airport) is also indicated. Source: self constructed using data from OpenStreetMap via GeoFabrik downloaded on 28 May, 2020 and plot style by Luiz Andrade.



**Figure 1.** Locations of the suburban (Bremen H-L) and rural (Seebergen) measurement sites in Bremen.

|               | Bremen H-L | Seebergen |
|---------------|------------|-----------|
| Latitude (°)  | 53.1038    | 53.1363   |
| Longitude (°) | 8.8498     | 8.9851    |
| Elevation (m) | 22         | 11        |

**Table 1.** List of Bremen night sky monitoring sites.

Two measurement sites were chosen for this study. The chosen suburban site is situated on the roof of the U-Building of the Faculty of Physics and Electronics of the University of Bremen in the district Horn-Lehe (hereafter Bremen H-L using the site naming scheme in Kyba et al. (2015)). There are some exterior lightings used at the Universum Bremen (a science museum) and at the drop tower approximately 900 m away from the measurement site, however these light sources are not directed to the site and considering the sensitivity of the SQM close to the horizon, no effect is expected on the measured radiance. Moreover, no direct light sources are present at the site during night time. Another site in the village Seebergen in the municipality Lilienthal is a family house situated next to the northern boundary between Bremen and the federal state Lower-Saxony. The village is not close to other significant light sources, since it is at least more than 1 km away from the other villages, and the

roads connecting them are not illuminated. Compact florescent light luminaires are the dominant type of public lighting inside the village, apart from several HPS street lamps. There is a tree to the southwest of the SQM, which was growing over time. However It did not enter beyond 40° during the measurement period.

### **Instruments**

The SQMs we used in this study is of the LE (lens ethernet) variant with plastic lens and ethernet adaptor, which is able to upload measurement data to a remote client. The plastic lens reduces the full-width-half-maximum (FWHM) field of view to 20°, and there is an infrared filter in front of the sensor. The details about the SQM-LE can be found in CINZANO (2007).

The spectral response of the SQM's combination of photodiode sensor and infrared filter is described to be approximately matching the photopic vision of the human eye, with a wavelength of peak sensitivity at 540 nm. The SQM reports the measured radiance in the unit of mag/arcsec<sup>2</sup>, a logarithmic unit used in astronomy with the radiance value of the star Vega as the reference. It is defined as

$$L_m = -2.5 \log \frac{L}{L_0} \quad L_m = -2.5 \log \frac{L}{L_0}$$

where  $L$ , the radiance of the object, is in the unit of cd/m<sup>3</sup> the and  $L_0$  is the Radiance of Vega. However, since the SQM has a different spectral response with most standard spectral response functions used in photometry and astrometry (CINZANO, 2007), we denote the radiance readout by the SQM as mag<sub>SQM</sub>/arcsec<sup>2</sup>.

The devices were placed inside waterproof housings with a glass window at the top, as the SQM was not waterproof. The glass window was sealed with, according to the manufacturer, by marine-grade silicone sealant. However, the sealant usually failed after several years, possibly due to the difference in expansion coefficient between the glass window and the housing body, which is made of PVC, under outdoor thermal stress. In this case sealant was reapplied and tested before reinstalling to the measurement sites. Also, the attenuation of the housing window was checked once per year or after resealing, and was found to be within 5% from the specifications of the manufacturer. Constant glass window attenuation values in mag<sub>SQM</sub>/arcsec<sup>2</sup> are used for the whole dataset.

The SQM-LEs were installed at the location Bremen-HL in December, 2011 and at Seebergen in February, 2012, respectively. Both were set to continuously measure at an interval of once per minute, except when there were technical problems (e.g. power outage, water ingress due to housing window sealing failure or network interruption).

The cloud coverage condition was determined by the weather data from the weather station of the Bremen City Airport (WMO index number 10224, coordinates 53.05°N, 8.80°E), situated approximately 7.4 km from Bremen H-L and 16.1 km from Seebergen. A meteorologist from the German Weather Services (DWD) observes the sky condition once every hour. Gaps of observations sometimes occurred at 21:00 and 2:00 UTC.

### ***Data processing and analysis***

The acquired data was first screened by the maintenance log for undesired factors which may affect the readings, for example bird droppings on the housing window or water ingress into the housing, or events like ray of skybeamer entering the field of view. The acquired data from mid-2016 to mid-2017 were not used because of extended downtime at Seebergen during winter 2016–17.

The processing chain, performed mainly using the NumPy library for Python, follows in general the procedure described in KYBA et al. (2015), and is outlined as follows. To remove the influence of the other stable natural light sources, we do not use data points when the solar elevation angle was higher than  $-18^\circ$  which is the definition of astronomical twilight, or when the moon was above the horizon. While the acquisition rate of data was set to once per minute, the dataset was rebinned and mean value per minute was calculated, to prevent the rare cases of multiple reading within a minute, which can be caused by network response latency. The center of each one-minute bin was at the 30th second.

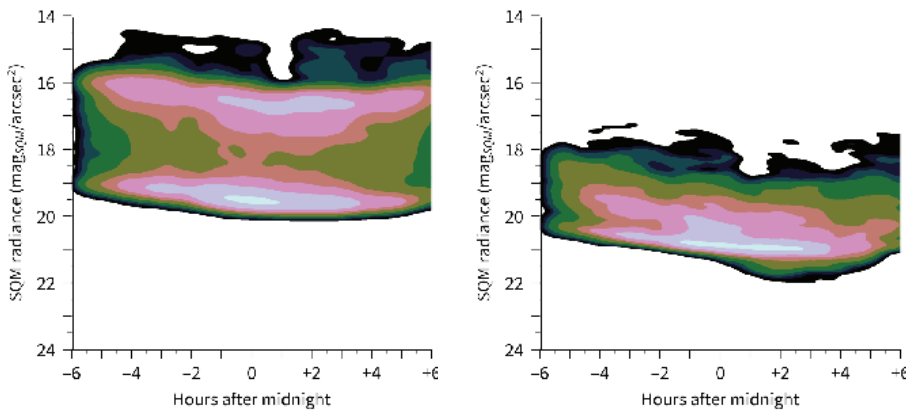
The resulting subset of data were used to generate a set of visualizations. First, the overall distribution of radiance with respect to the time of the day was calculated for each site and used to produce a contour plot in terms of relative frequency, which was done by using a kernel density estimator. Second, for each 30-minute period, a time series of nightly median sky radiance was produced for clear and overcast sky using the weather data with extra constraint in variation of individual measurements. The maximum standard deviation for each daily sky radiance was set to  $0.15 \text{ mag}_{\text{SQM}}/\text{arcsec}^2$  for clear sky and  $0.19 \text{ mag}_{\text{SQM}}/\text{arcsec}^2$  for overcast sky. Linear fits in  $\text{mag}_{\text{SQM}}/\text{arcsec}^2$  per annum, which is in effect a logarithmic fit, were then calculated for daily radiance values taken from September 2012 to June 2016. For convenience, the unit of the fit was converted into percent per annum.

### ***Comparison with VIIRS-DNB monthly composite satellite data***

The time series of the nearest respective pixels from the ground points of both sites taken by the Visible/Infrared Imaging Radiometer Suite Day/Night Band (VIIRS-DNB) on board the Suomi National Polar-orbiting Partnership (S-NPP)

satellite was downloaded for the monthly composites generated by the Earth Observation Group (EOG) with outliers and data points flagged by the cloud mask removed, using the webapp Light Pollution Map (LIGHTTRENDS). Only data from the end of 2012 (the starting period of available Version 1 monthly composite data) to the end of 2016 were selected to match the measurement period to the greatest extent as possible. The data from the nearest grid cells of the respective measurement sites were selected. The site Bremen H-L is enclosed by the area of the grid cell (53.104°N, 8.850°E), whereas the site Seebergen is not, and the neighboring grid cell in the southwest direction (53.133°N, 8.979°E) was instead selected. Logarithm of the radiance was used to produce a semi-logarithm fit to yield a rate of change in percent per annum.

**Results**

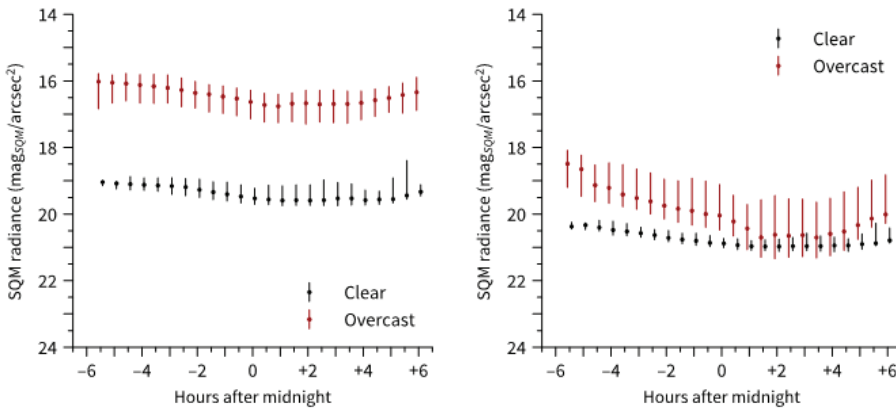


**Figure 2.** Contour plots for measurement sites Bremen-HL (left) and Seebergen (right).

Only measurements taken between December 2011 and June 2016 without astronomical twilight and moonlight were used to generate the composite data. Source: TONG (2016)

Figure 2 shows the distribution of the night sky radiance with respect to hours from local midnight as contour plot, which is normalized relative to the area of highest density in number of data points. The two sites show different sky radiance patterns. In Bremen H-L, a bimodal distribution can be seen throughout the whole night, which corresponds to clear nights for the peak of lower sky radiance, and cloudy to overcast nights for the higher sky radiance (Figure 3, left). In Seebergen, the two modes are only discernible during the early hours of the night, and then becomes unimodal after the midnight. Also noticeable is that the sky radiance of Seebergen is lower than that of Bremen H-L. For example, the median clear sky radiance at Bremen H-L is  $19.53^{+0.18}_{-0.31}$  mag<sub>SQM</sub>/arcsec<sup>2</sup>, whereas that of Seebergen is  $20.88^{+0.13}_{-0.15}$  mag<sub>SQM</sub>/arcsec<sup>2</sup>,

a factor of 3.47. The brightening by backscattering of clouds are also different: the night sky was brighter by a factor of 2.17 at Seebergen and 14.45 at Bremen H-L.

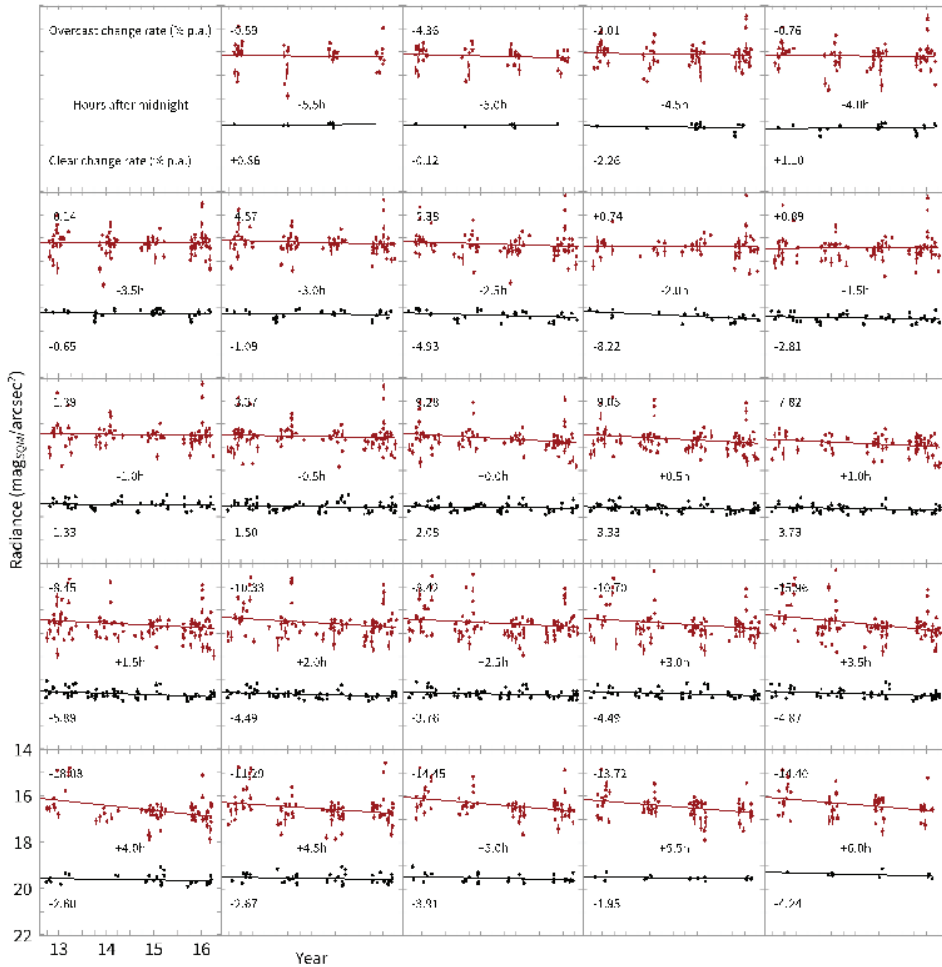


**Figure 3.** Contour plots for measurement sites Bremen-HL and Seebergen. Only measurements taken between December 2011 and June 2016 without astronomical twilight and moonlight, and with cloud coverage data from weather station are used to generate these plots. Error bars are values at  $\pm 1\sigma$ . Source: Tong (2016)

Figure 3 also shows a trend of decreasing sky brightness from early evening to late midnight, both for the sites Bremen H-L and Seebergen and for both clear and overcast sky. In Bremen H-L, the sky radiance dropped by approximately 40% and 50% for clear and overcast sky, respectively, from 18:30 to 1:00, whereas in Seebergen the decreases were 45% and 87% for respectively the clear and overcast sky during the same period of night. In Seebergen, the  $-1\sigma$  values for overcast nights were lower than that of the clear nights, which may indicate that in some cases, the presence of clouds *darkened* the sky at zenith, which is the opposite of the situation in suburban areas like Bremen H-L, although whether this happens may depend on other factors such as the droplet size distribution and cloud base height.

Figures 4 and 5 show how the sky radiances changed in long term with respect to different hours of the night, for both clear and overcast periods, and Figure 6 shows the rates of change per year with respect to hour of the night, as shown in Figures 4 and 5. For Bremen H-L, no significant changes except between 21:30 and 22:00 during clear night could be seen for the first half of the night.





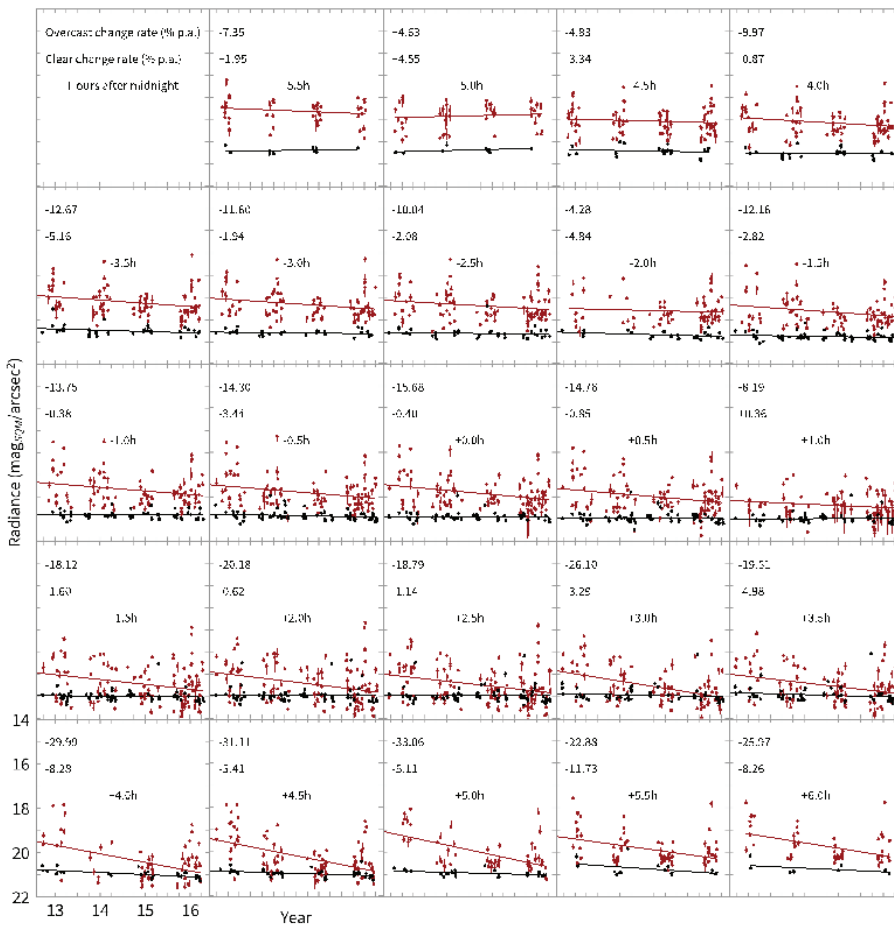
**Figure 4.** Trends of daily averaged sky radiance at Bremen H-L during clear (black) and overcast (red) periods for each 30-minute period of the night.

Only data from September 2012 to June 2016 with corresponding weather data from weather station were used for intercomparison purpose with Figure 6. Thresholds in daily variation are used as an extra measure for weather screening. The quantities and scaling of all subplots are identical for intercomparison. Logarithmic fits are displayed by straight lines, with annual rates of change in percent shown in each subplot. Source: Tong (2016)), with additional time range constrain.

At midnight and thereafter a decrease in sky radiance can be seen both during clear and overcast periods in Bremen H-L, with the rate of decrease of up to 5.9% per annum (at 1:30) during clear nights, and 18.1% per annum (at 4:00) during overcast nights. Seebergen does not show significant decrease during clear periods until 3:00, after which a rate of decrease up to 11.7% per annum (at 5:30) can be observed. However, a rapid decrease of up to 33.1% per annum (at 5:00) can be seen during overcast nights.

Figure 7 shows the monthly averaged sky radiances of both sites from September 2012 to June 2016, together with an exponential fit for each set of data. The data is filtered by the cloud screening algorithm of the EOG to reduce the chance of cloud contamination of dataset. It should be noted that the overflight time of the Suomi NPP is centered around 2:00 UTC (3:00 during CET, 4:00 during CEST) in western Europe, and with an orbital period of 101.8 minutes it means that the overflight time can be approximately 1 hour and 40 minutes earlier or later at maximum (TONG et al. 2020).

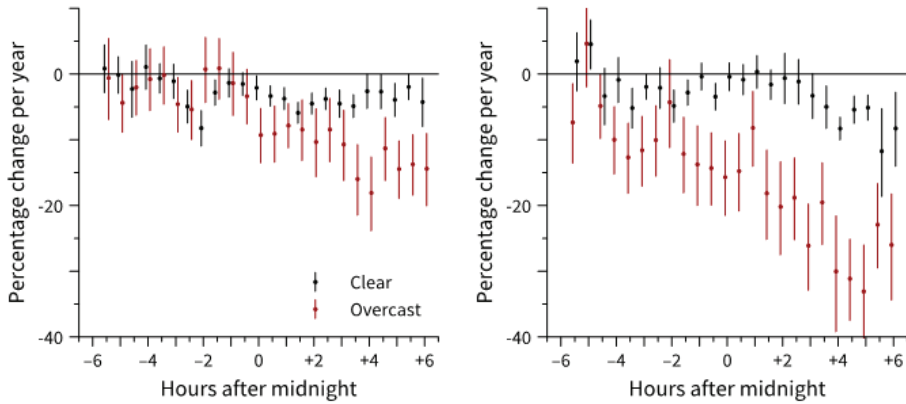
A trend of decrease in both sites were observed. The rate of decrease in Bremen H-L was lower (1.39%) than that of Seebergen (8.59%). However, these are associated with high uncertainty: the p-value for the Bremen H-L fit is 0.742, and that of Seebergen is 0.229.



**Figure 5.** Trends of daily averaged sky radiance at Seebergen during clear (black) and overcast (red) periods for each 30-minute period of the night.

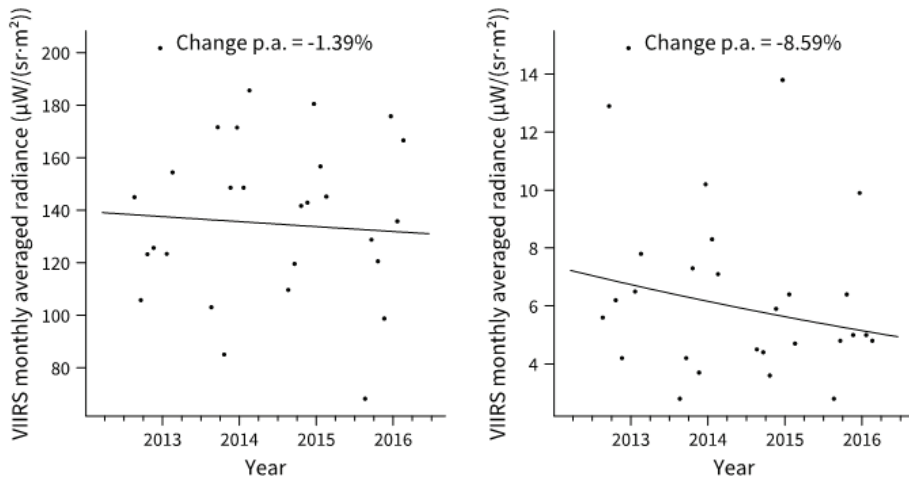
Only data from September 2012 to June 2016 with corresponding weather data from weather station were used for intercomparison purpose with Figure 6. Thresholds in

daily variation are used as an extra measure for weather screening. The quantities and scaling of all subplots are identical for intercomparison. Logarithmic fits are displayed by straight lines, with annual rates of change in percent shown in each subplot. Source: Tong (2016), with additional time range constrain.



**Figure 6.** Rate of change per year of night sky radiance for clear (black) and overcast (red) nights for each 30-minute period at Bremen H-L (left) and Seebergen (right) using data from Figures 4 and 5.

Only data from September 2012 to June 2016 with corresponding weather data from weather station were used for intercomparison purpose with Figure 6. Thresholds in daily variation are used for additional weather screening. Source: Tong (2016), with additional time range constrain.



**Figure 7.** Monthly VIIRS–DNB composite radiance data for Bremen H-L (left) and Seebergen (right).

The grid cell enclosing Bremen H-L is selected, while the neighboring grid cell in the southwest direction of Seebergen is chosen instead, due to unavailability of data. Only data taken from September 2012 to June 2016 were used. Note the different scale in y-axis. Source: Earth Observation Group, Colorado School of Mines via Lightpollutionmap.info.

## Discussion

The bimodal distribution of Bremen H-L in sky radiance throughout the night indicates that the night sky of site is typical for suburban or urban areas. At the presence of artificial light emitting from the ground, clouds act as a backscattering medium, brightening the sky.

In contrast, Seebergen experienced less brightening during the early hours of the night, and may have seen darkening by the presence of clouds during later hours of the night. A curfew is implemented in Seebergen between 1:00 and 4:00 local time (which changes accordingly when daylight saving time begins or ends), during which the local contribution of artificial light is reduced, which in turn may be the cause of the significantly decreased sky radiance at that period of the night, and the possibility of cloud coverage darkening the sky instead of brightening as observed in Bremen H-L.

The results from the S-NPP VIIRS-DNB monthly composite show discrepancy with the ground-based SQM data which, whereas the rate of decrease in clear sky radiance in Bremen H-L is higher than that of Seebergen except at after approximately 4:00, the rate of decrease observed by VIIRS-DNB was higher in Seebergen. As noted earlier, however, both fits have high uncertainties with high associated p-values, which may be caused by the variation of the monthly averaged radiance data. Some of the sources of these uncertainties include the angular and temporal dependence of emissions from artificial light sources (TONG et al., 2020), as well as variations in surface albedo.

### ***Limitations of SQM and VIIRS-DNB measurements***

While the time span of 4.5 years of the SQM measurements is useful in a way that we are able to observe changes in night sky radiance for both suburban and rural locations in Bremen, the exact sources of the decrease in sky radiance cannot be determined due to the following reasons:

The SQM is a single point, wide field of view measurement device, meaning that it is not possible to spatially resolve the angular distribution of radiance, and hence also not possible to pinpoint and quantify the temporal changes of individual sources of artificial light.

In addition to the single angle measurement for the SQM, its optical system is susceptible to mechanical shock, making it impossible to metrologically calibrate for spectral and angular response.

Although the VIIRS-DNB sensor is capable of making observations from multiple angles, this cannot be used to compare the results from the SQM due to

Since the SQM is a broadband radiometer, it is not able to distinguish the difference between a change in spectral distribution or a change in intensity, for example remodeling of public lighting from high pressure sodium-based

to LED-based system. VIIRS–DNB observations suffer also from this, as the sensor’s main purpose is cloud cover observation in visible and near infrared regime and not artificial light observations. In addition, the sensitivity of the VIIRS–DNB sensor is negligible for blue light with a wavelength below 490 nm, further limiting its use for detecting transition to LED-based public lighting.

As a result of having no quantitative measurement by means of imaging, while there are speculations that the decrease of sky radiance is due to the reduction of output power from the public lighting system as a result of aging (KYBA et al., 2017), no direct evidence can be found as of this writing.

## **Conclusion**

This article shows that a simple, inexpensive radiometer like the SQM can be used to observe long-term change of night sky radiance. Using two SQMs, we were able to show that suburban area of the city of Bremen shows a different pattern in night sky radiance: the backscattering of artificial light by clouds brightens the night sky more severely in suburban area than in rural area, and darkening of the sky is seen instead in the rural site during the hours of curfew of local public lightings. In addition, we were able to observe changes in sky radiance for different period of the night over the span of 4.5 years, with most of the periods showing either insignificant change or decrease of sky radiance. However, without time series of night sky images, we are unable to determine the cause these changes, and whether the observed changes were caused by other factors such as change of emission spectrum of artificial light sources.

We have also compared the results from the SQM sky radiance data with the monthly composite data from VIIRS–DNB. Although a general trend of decrease was observed in both sites, the p-values and hence the uncertainty of the fit are large, and there was an inconsistency when compared with the SQM data.

The results demonstrate that while SQM measurements can provide useful information about long-term changes in zenith sky radiances, they cannot be used to pinpoint the sources of the detected changes. Therefore, in light of the recent advances of inexpensive, commercially available digital cameras, which are able to perform continuous, spatially and spectrally resolved night sky measurements, allsky imagery with RGB sensing capability should be deployed for future long-term measurements of night sky.

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