Article

Interference of Meteorological Variables on Night Sky Observation in Rural and Urban Zones of South-Western Spain

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Abstract: Several factors affect the visibility of the night sky, most significantly artificial light at night (ALAN), meteorological conditions and Moon illumination. There are few studies that analyse the effect of meteorological conditions and Moon illumination, especially in rural areas (where the ALAN level is lower). An analysis of these variables could be relevant for sky observation, especially for astronomical observatories, usually located in rural areas with low ALAN. Knowledge of the relevant variables in the observation allows for the correct planning of the observation. The observer can consult meteorological agencies for forecasts of these variables, allowing him to know in advance whether the observation will be carried out under optimal conditions. In this study, a photometer and a weather station were installed in various municipalities located in rural areas of south-western Spain. This equipment was also installed in the city of Badajoz (urban area with high ALAN). These devices carried out simultaneous measurements of night sky darkness (NSB) and meteorological conditions for a period of approximately 6 months. A statistical analysis of the recorded data was carried out. Only the Moon illumination was slightly correlated with NSB in both cases (-0.3 in rural areas and -0.35 in urban areas). Sky temperature only proved a correlation with NSB in the urban area (-0.41). The correlations indicated are significant at the 0.01 level. The results obtained in the urban area were confirmed by a second analysis using meteorological data provided by a meteorological agency, obtaining similar results. A web application was developed that allows for real-time consultation of NSB and meteorological data for each area, which can help observe the starry sky. Globally, the results obtained in this study could help in the planning of stargazing in both urban and rural areas, allowing one to know in advance if weather conditions would affect the perception capacity.

Keywords: observatories; weather; stargazing; moon; astro-tourism; NSB; photometer; ALAN; sky quality meter; night sky

1. Introduction

When observing the sky, there is the problem of not knowing whether the observation will be carried out under optimal conditions [1]. The visibility of stars in the night sky is mainly affected by urban night-time light pollution (ALAN), the weather conditions and the Moon phase [1–8]. The ALAN influence on the night sky darkness level (NSB) has been extensively studied [4,5,9–18]. By correctly selecting the observing site (setting it in a low-brightness place, usually far from urban centres) and a proper design of the illumination of the area [6,17], it is possible to minimise the ALAN interference. The presence of the Moon may also be reliably determined depending on the Moon phase at the time of observation. By selecting the days with a Moon phase close to the new Moon, the level of brightness due to its reflection can be minimized [1].

Weather conditions beyond the observer's control and may interfere with observation [1,19–23]. However, with today's technology it is possible to predict, with a certain degree of reliability, future weather conditions (within a given time frame).

In this sense, several studies analyse the influence of weather conditions on the level of night-time darkness in urban environments [2–4,19,24]. However, there is a high level of ALAN in these locations, which may interfere with the results obtained. In areas without a high level of ALAN, e.g., rural areas far from the main population centres, it is possible to study the meteorological influence on the level of darkness without the influence of ALAN. In this respect, there are fewer studies assessing the influence of climatic conditions in these areas.

A detailed investigation in these areas could reveal which meteorological variables affect the observation and the level of interference they exert. From this information, it is possible to plan the observation properly. The observer can check the forecast of these variables at the meteorological agencies in advance and know whether the observation will take place under optimal conditions. This information can help skywatchers (astronomers, astro-tourists, etc.), allowing them to observe under optimal conditions [1,23].

Therefore, the novelty of this study is to evaluate the influence of meteorological conditions on the observation of the starry sky in rural areas (low ALAN conditions) and compare them with those obtained in urban areas (high ALAN conditions). For this purpose, it is necessary to analyse the atmospheric variables (sky temperature, ambient temperature, humidity, relative pressure, wind speed, dew point and hourly rainfall) and, simultaneously, the level of darkness of the sky to calculate the correlation between them. The measurement of these parameters requires the use of a photometer together with a weather station for simultaneous recording. Through further analysis, it is possible to carry out a comparison between them. This study could help in the planning of stargazing in both urban and rural areas, allowing to know in advance the influence of meteorological conditions on the quality of the observation to establish optimal viewing conditions.

2. Materials and Methods

In order to determine the interference generated by the meteorological variables, it was necessary to measure the NSB in mag/arcsec^2. A higher value of this magnitude will imply a higher level of darkness of the night sky, associated with a lower level of light pollution, which will allow for better observability of celestial bodies. A higher NSB value is linked to a lower level of light contamination, which allows a better perception of the stars. The registration of NSB was performed using a Sieltec Canarias SKYGLOW photometer (Appendix A [25]).

Depending on the magnitude level, the observer will be able to appreciate a wider range of celestial objects. The NSB should reach a value as high as possible, up to a maximum of 24 mag/arcsec^2 [18], where visibility is perfect. Simultaneously with the above measurements, a Davis Vantage Vue weather station (Appendix A [26]) was recording the atmospheric conditions in the area. The atmospheric variables analysed in the study were as follows:

- Sky temperature (°C);
- Ambient temperature (°C);
- Relative humidity (%);
- Relative pressure (hPa);
- Wind speed (km/h);
- Dew point (°C);
- Hourly rainfall (mm).

A number of other secondary variables were measured, which were discarded from the analysis as they did not directly influence the quantification of the measured brightness (e.g., wind direction) or were directly dependent on other measurements (e.g., wind chill). As for cloudiness, the in-house team did not carry out this measurement, so the data available for the study were provided by AEMET [27]. Meteorological and night sky

darkness data were collected simultaneously so that a comparison between the two could be made later and their possible correlation established.

2.1. Research Area

The best sites for sky observation are normally placed away from large cities [18,28]. Various rural villages in the province of Cáceres were selected for the experimental phase. This study is part of the GLOBALTUR EUROACE [29] project that promotes tourism development in the Tejo/Tajo International Biosphere Reserve (Figure 1). The selected municipalities were: Zarza la Mayor, Herreruela, Valencia de Alcántara, Membrío, Salorino, Brozas, Alcántara, Carbajo, Herrera de Alcántara and Santiago de Alcántara.
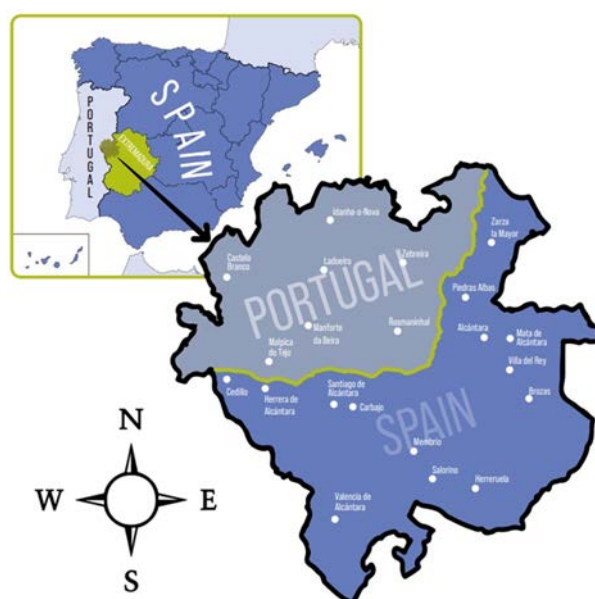

Figure 1. Localisation of the Tejo/Tajo International Biosphere Reserve [30].

Additionally, a grouping of different municipalities geographically close to each other was carried out in three different areas, A (Herreruela, Salorino, Valencia de Alcántara and Membrío), B (Cedillo, Herrera de Alcántara, Santiago de Alcántara and Carbajo) and C (Alcántara, Brozas, Piedras Albas and Zarza la Mayor). In addition, data were collected at the Industrial Engineering School (University of Extremadura) in Badajoz. In this way, data were available for both rural and urban areas.

To avoid the influence of the municipality's lighting, the photometers were placed on the outskirts. In the towns of Cedillo and Valencia de Alcántara, the measuring devices had to be located within the municipality due to the poor coverage present in the area. The coordinates and NSB level in the zone are detailed in Appendix B.

3. Results

At the beginning of the project, a weather station along with a photometer was moved to each of the different rural municipalities indicated in Section 2.1 for one week. This equipment allowed the simultaneous recording of NSB and meteorological conditions. Based on these data, a municipality was selected as representative of the meteorological conditions in each of the zones. Specifically, the municipalities selected as representatives of their area were Herreruela (Zone A), Santiago de Alcántara (Zone B) and Zarza la Mayor (Zone C). In each of these zones, a photometer was placed together with a meteorological station for approximately 6 months (from 14 February 2022 to 26 August 2022).

Similarly, a photometer and a weather station were installed at the School of Industrial Engineering (University of Extremadura) in Badajoz, which collected data from

22 February 2022 to 25 August 2022. This equipment allowed data to be collected in an urban area, for later comparison with data collected in rural areas.

The NSB and meteorological data recorded in rural and urban areas were used for the statistical analysis and can be found in the following handle [31]. As an example, the values of the NSB recorded during the first week in the different municipalities have been plotted in Figures 2–12. The y-axis shows the evolution of the night-time brightness detected using the photometer (NSB) in mag/sg arcsec^2. The abscissa axis (x-axis) shows the date at which the measurement was taken. Each date corresponds to the set of hours between 10 p.m. and 7 a.m.
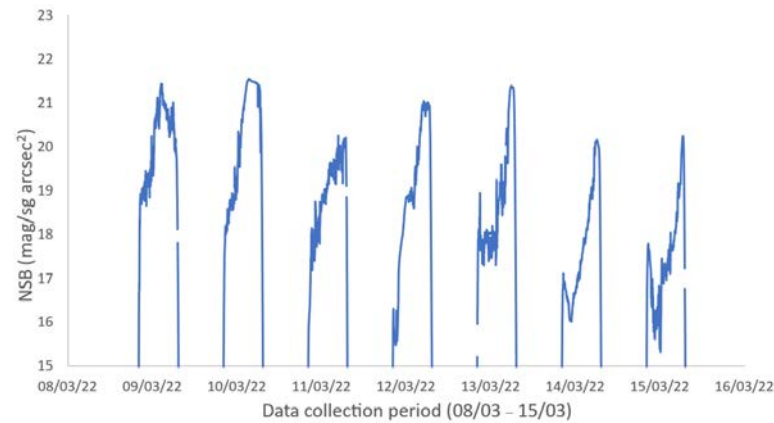

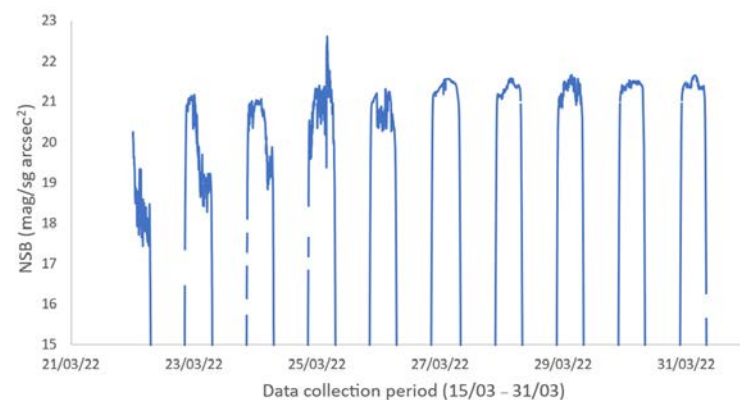**Figure 2.** NSB registered in Zarza la Mayor.
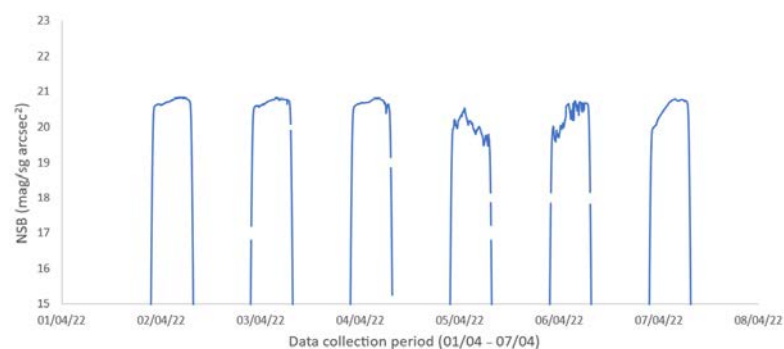

Figure 3. NSB registered in Herreruela.

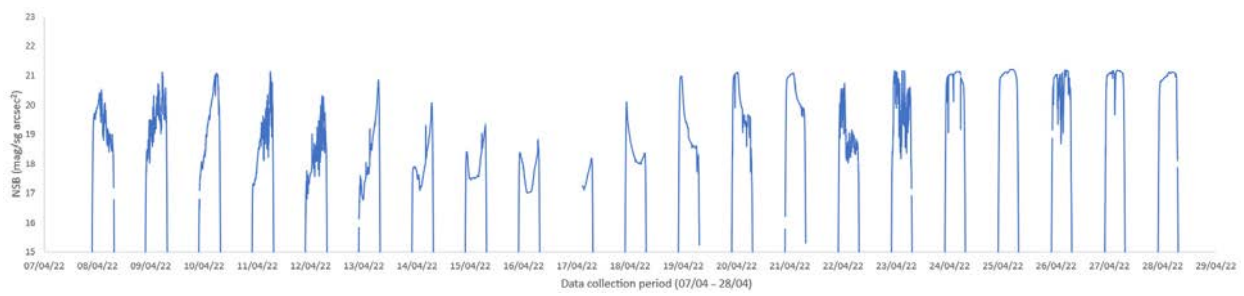**Figure 4.** NSB registered in Cedillo.

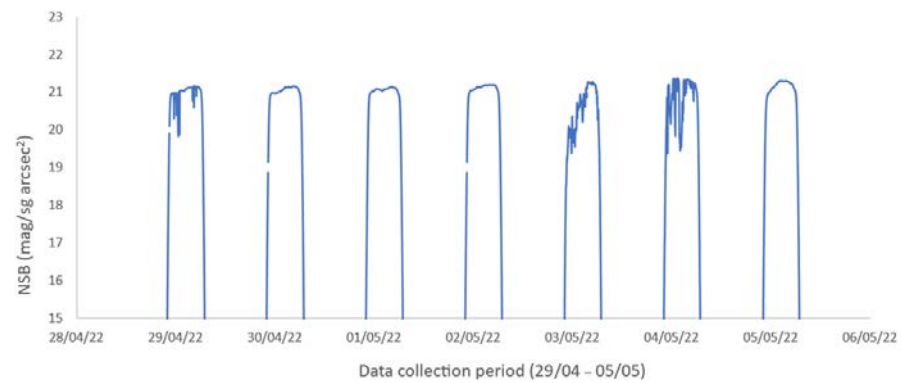**Figure 5.** NSB registered in Valencia de Alcántara.

Figure 6. NSB registered in Membrío.
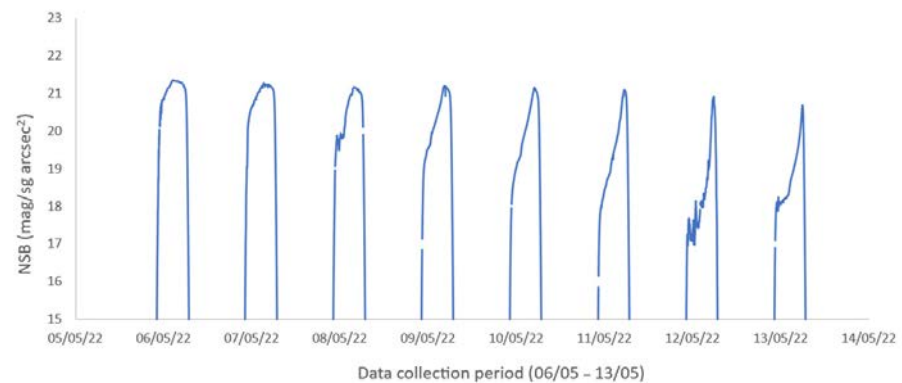
Figure 7. NSB registered in Salorino.
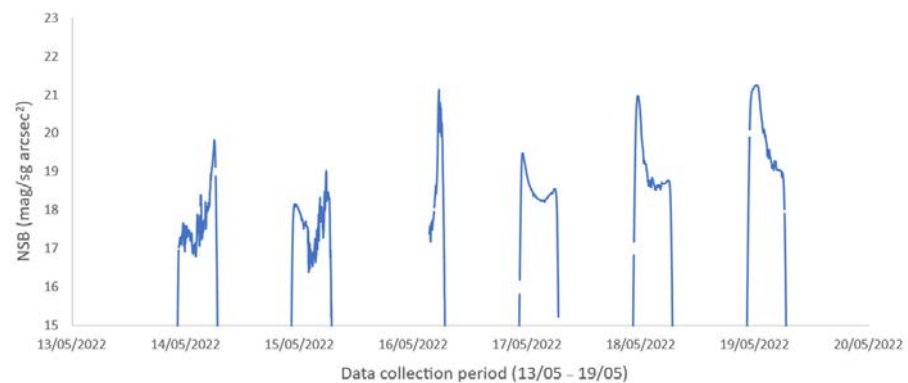
Figure 8. NSB registered in Brozas.
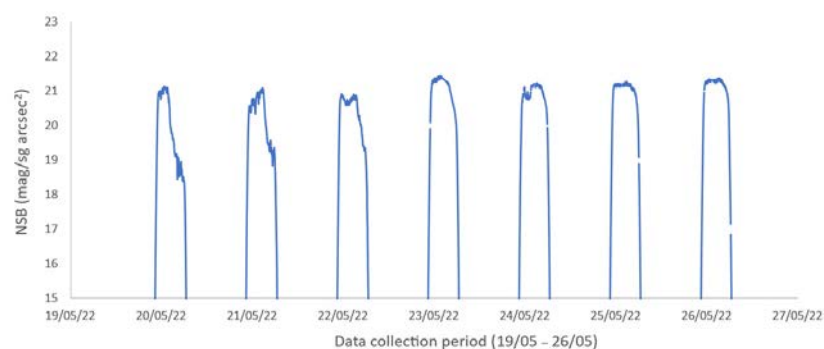
Figure 9. NSB registered in Alcántara.

Figure 10. NSB registered in Carbajo.

Figure 11. NSB registered in Herrera de Alcántara.

Figure 12. NSB registered in Santiago de Alcántara.

As can be seen in Figures 2–12, the NSB increases progressively from sunset to its maximum value before dawn twilight, at which point it begins to decrease. In some measurements, specifically those corresponding to the municipalities of Zarza, Brozas and

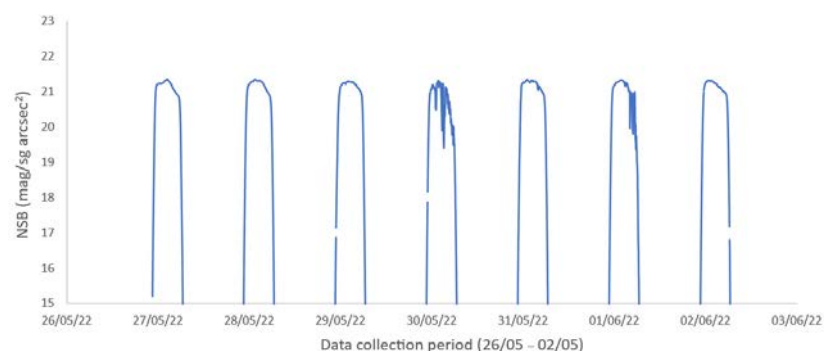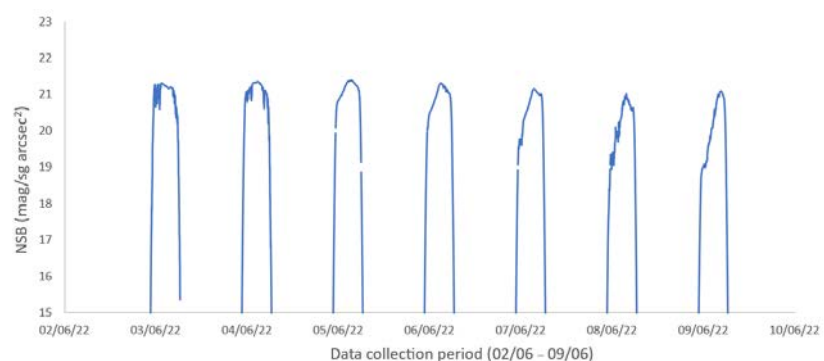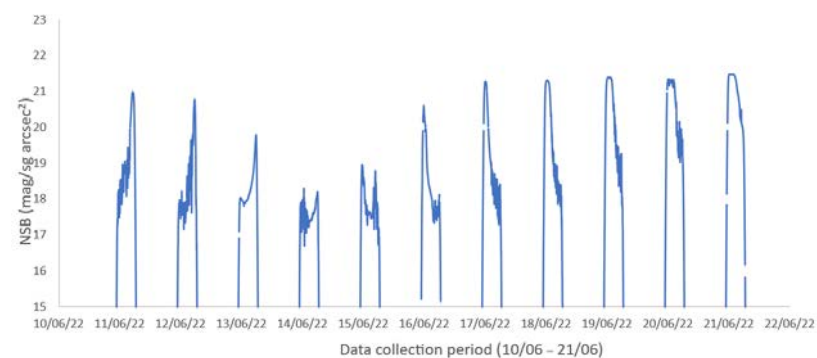Santiago de Alcántara, the NSB is significantly lower than the values reached on previous nights. This may mainly be due to two factors: the presence of the Moon and cloudiness. In both cases, the values recorded are irregular, with small fluctuations due to the variation in the relative position of these elements throughout the night. In those cases where the Moon is present, there is also an increase in the luminosity of the area, thus reducing the NSB values recorded.

A web application WeatherUEX [32] has been developed that allows real-time consultation of the level of darkness (NSB) and meteorological data recorded by the measurement equipment in each area, which allows data to be collected in the study area and could help in the observation of the starry sky.

4. Discussion

Once the data collection phase was completed, the data [31] were analysed. First of all, the data were downloaded from the server where they were stored and transformed from the original json data format (a format widely used for data exchange) to a format that allowed for them to be manipulated and analysed in a simpler and more accessible way (opting in this case for an xlsx format present in Microsoft Excel spreadsheets).

It was noted that the sampling period for data collection for each instrument was different. The weather station recorded data every 15 min, while the photometer recorded data every 5 min. In this case, the brightness data were more variable, especially at sunrise/sunset times. For this reason, each meteorological record was repeated three times, thus obtaining meteorological data every 5 min. In this way, the same amount of both meteorological and luminosity data was available, which was then merged into a single file.

The data collected were then filtered, eliminating those values corresponding to the hours of sunlight (between 7:00 h and 22:00 h), as they are not relevant for the study of the night darkness level. The data where there had been an error in the recording of any of the devices were also eliminated. Once these filters had been applied, the approximate number of measurements to be analysed was 28,000 for the whole of the different municipalities and 13,550 for the city of Badajoz, which allows for a solid database analysis to be carried out.

Using the MATLAB tool, the Pearson correlation matrix was calculated for the data recorded in the three zones A, B and C (all data taken in rural areas) and in the city of Badajoz (urban area). The correlation between the different variables analysed in the experiment was determined with Pearson's correlation matrix. Values of this matrix close to 1 imply a direct correlation between variables, and close to -1 an inverse correlation between variables. The results obtained are shown below, with those values associated with the NSB variable being particularly important. These values will allow us to determine those meteorological variables that have a decisive effect on the observation of the sky.

4.1. Comparison and Discussion of Results

The correlation values of the different variables with the NSB are marked in bold font. These are close to 0 in both rural (Table 1) and urban areas (Table 2), therefore, there is no significant correlation between the different meteorological variables measured with the level of night-time darkness. Only two variables are moderately correlated with the NSB: the sky temperature (-0.41 in urban areas) and the presence of the Moon (-0.3 in rural areas and -0.35 in urban areas).

With the available data, it is not possible to assume that the low correlation between the NSB and the sky temperature is due to causality between the two variables. It can be seen that, as the night progresses, less sunlight reaches the geographical point of data collection due to the Earth's rotational movement. This fact causes that, simultaneously, the level of darkness increases while the sky temperature drops, as the amount of light and heat provided by the Sun decreases. This could cause a correlation between the NSB and the sky temperature since both variables depend on the amount of solar radiation reaching the area.

Table 1. Pearson correlation matrix for rural areas (areas A, B and C combined). The correlation values of the different variables with the NSB are marked in bold font. The variables marked with an asterisk "*" have a significance level of 1%.

	NSB	ST	AT	H	RP	WS	DP	HR	M
NSB	**1**	**−0.11 ***	**−0.1 ***	**0.05 ***	**0.09 ***	**0.11 ***	**−0.06**	**−0.05 ***	**−0.3 ***
ST	−0.11 *	1	0.36 *	0.06 *	−0.14 *	−0.07 *	0.54 *	0.15 *	−0.06 *
AT	−0.1 *	0.36 *	1	−0.66 *	0.46 *	0.04 *	0.74 *	−0.02 *	−0.07 *
H	0.05 *	0.06 *	−0.66 *	1	−0.28 *	−0.26 *	0.02 *	0.08 *	−0.06 *
RP	0.09 *	−0.14 *	0.46 *	−0.28 *	1	−0.12 *	0.36 *	−0.21 *	0.1 *
WS	0.11 *	−0.07 *	0.04 *	−0.26 *	−0.12 *	1	−0.16 *	−0.03 *	0.1 *
DP	−0.06 *	0.54 *	0.74 *	0.02 *	0.36 *	−0.16 *	1	0.05 *	−0.02 *
HR	−0.05 *	0.15 *	−0.02 *	0.08 *	−0.21 *	−0.03 *	0.05 *	1	−0.03 *
M	−0.3 *	−0.06	−0.07 *	−0.06 *	0.1 *	0.1 *	−0.02 *	−0.03 *	1

The following acronyms have been used for the variables analysed: Sky temperature (ST), ambient temperature (AT), humidity (H), relative pressure (RP), wind speed (WS), dew point (DP), hourly rainfall (HR), Moon (M).

Table 2. Pearson correlation matrix of an urban area (Badajoz). The correlation values of the different variables with the NSB are marked in bold font. The variables marked with an asterisk "*" have a significance level of 1%.

	NSB	ST	AT	H	RP	WS	DP	HR	M
NSB	**1**	**−0.41 ***	**0.09 ***	**−0.17 ***	**0.15 ***	**−0.01**	**−0.01**	**−0.14 ***	**−0.35 ***
ST	−0.41 *	1	0.62 *	−0.27 *	−0.3 *	0.07 *	0.6 *	0.06 *	−0.2 *
AT	0.09 *	0.62 *	1	−0.84 *	−0.18 *	0.15 *	0.5 *	−0.09 *	−0.2 *
H	−0.17 *	−0.27 *	−0.84 *	1	0.07 *	−0.11 *	0 *	0.13 *	0.09 *
RP	0.15 *	−0.3 *	−0.18 *	0.07 *	1	−0.24 *	−0.18 *	−0.07 *	0.03
WS	−0.01	0.07 *	0.15 *	−0.11 *	−0.24 *	1	0.17 *	0.02 *	0.09 *
DP	−0.01	0.6 *	0.5 *	0 *	−0.18 *	0.17 *	1	−0.01	−0.22 *
HR	−0.14 *	0.06 *	−0.09 *	0.13 *	−0.07 *	0.02 *	−0.01	1	−0.03 *
M	−0.35 *	−0.2 *	−0.2 *	0.09 *	0.03	0.09 *	−0.22 *	−0.03 *	1

The following acronyms have been used for the variables analysed: Sky temperature (ST), ambient temperature (AT), humidity (H), relative pressure (RP), wind speed (WS), dew point (DP), hourly rainfall (HR), Moon (M).

As for the presence of the Moon, in those phases in which the Moon is full (full Moon), the existing brightness level is higher, which causes a decrease in the NSB. This fact is reflected in the results obtained, as there is an inverse relationship between the NSB and Moon phase variables, namely −0.3 in rural areas and −0.35 in urban areas. This result is similar to that provided by other authors, specifically Ref. [2] establishes a correlation of −0.271 between both variables and Ref. [33] one of −0.225, in the same meteorological conditions as this study (clear sky). As for the average NSB values recorded under full Moon conditions, Ref. [34] establishes a value between 18 and 18.5 mag/arcsec^2 for urban environments (Berlin). Other authors [10] set the NSB level of the urban night sky at between 16.8 and 19.2 mag/arcsec^2. These values are correctly matched with the average NSB value of 18.24 mag/arcsec^2 recorded in an urban environment (Badajoz) in this experiment.

In this sense, Ref. [34] provides a slightly lower value of 17.3 mag/arcsec^2 in the same conditions, but for a rural environment (Dachstein plateau, Alps). The authors of [10,35] establish values in rural areas between 19 and 21.6 mag/arcsec^2. The average recorded in rural environments and full Moon and clear sky conditions of this experiment was 19.52 mag/arcsec^2, coinciding with the range established by [35]. The discrepancy with [34] may be due to differences in measurement conditions.

4.2. Contrast of Results

To compare these results, the AEMET was asked for the historical meteorological data recorded both in the different rural areas and Badajoz city. This agency had data recorded

in Badajoz city. The agency did not have data on the rural municipalities. For this reason, only the data obtained in Badajoz city could be compared.

A new comparison was made between the data recorded by our photometer and the meteorological conditions recorded by the AEMET in the city of Badajoz, which allowed for a much broader analysis to be carried out, as data was available for a longer period, specifically from 10 May 2021 to the present day. The data provided by AEMET also included measurements of cloudiness in the area. To increase the reliability of the study, it was decided to eliminate those data that had been taken under cloudy conditions, that is, with cloudiness values above four-eighths of an overcast sky [36], since the presence of clouds prevents the visualisation of the starry sky [4,21,24,37–40], also increasing the glow level due to the greater scattering of light. Additionally, the different Moon phases were also included in the study, to evaluate how the presence of the Moon affected the NSB. Once these new filters were applied, together with those initially proposed, the total number of measurements to be analysed was approximately 51,000. The results of this analysis are shown in Table 3.

Table 3. Pearson correlation matrix of Badajoz city with AEMET data. The correlation values of the different variables with the NSB are marked in bold font. The variables marked with an asterisk "*" have a significance level of 1%.

	NSB	ST	AT	H	RP	WS	DP	HR	M
NSB	**1**	**−0.3 ***	**0**	**−0.13 ***	**−0.01 ***	**−0.08 ***	**−0.06 ***	**−0.14 ***	**−0.48 ***
ST	−0.3 *	1	0.68 *	−0.2 *	−0.51 *	0.05 *	0.77 *	0.14 *	0.06 *
AT	0	0.68 *	1	−0.71 *	−0.68 *	0.22 *	0.86 *	0.04 *	0
H	−0.13 *	−0.2 *	−0.71 *	1	0.38 *	−0.17 *	−0.32 *	0.07 *	0.02 *
RP	−0.01 *	−0.51 *	−0.68 *	0.38 *	1	−0.24 *	−0.64 *	−0.08 *	0.01 *
WS	−0.08 *	0.05 *	0.22 *	−0.17 *	−0.24 *	1	0.12 *	0.05 *	−0.04 *
DP	−0.06 *	0.77 *	0.86 *	−0.32 *	−0.64 *	0.12 *	1	0.08 *	0.01 *
HR	−0.14 *	0.14 *	0.04 *	0.07 *	−0.08 *	0.05 *	0.08 *	1	−0.02 *
M	−0.48 *	0.06 *	0	0.02 *	0.01 *	−0.04 *	0.01 *	−0.02 *	1

The following acronyms have been used for the variables analysed: Sky temperature (ST), ambient temperature (AT), humidity (H), relative pressure (RP), wind speed (WS), dew point (DP), hourly rainfall (HR), Moon (M).

The results obtained in Table 3 are similar to those obtained in Table 2, where the analysis was performed with the meteorological data. In both analyses (Tables 2 and 3) the only variables correlated with the NSB are sky temperature (−0.41 in Table 2 and −0.3 in Table 3) and illumination due to the Moon (−0.35 in Table 2 and −0.48 in Table 3). Given these results, it is possible to corroborate the conclusion obtained in Section 4.1.

Finally, the agreement between the data recorded using our equipment and the data provided by AEMET was evaluated to verify the validity of the data recorded using our measuring equipment (Table 4).

Table 4. Correlation between the meteorological data recorded with our own equipment and the data provided by AEMET. The variables marked with an asterisk "*" have a significance level of 1%.

Variable	Pearson's Correlation Coefficient
Relative pressure	0.88 *
Ambient temperature	0.98 *
Humidity	0.98 *
Dew point	0.98 *
Wind speed	0.75 *

The data recorded by our meteorological teams show a high correlation with the data provided by AEMET, thus verifying the validity of the analysis carried out in Section 4.1.

The small differences between the results obtained in Tables 2 and 3 may be due precisely to the fact that the correlation between the two data records is not perfect.

5. Conclusions

The influence of the different meteorological variables on the darkness level in the observation zone of rural areas (low ALAN) and urban areas (high ALAN) was evaluated. Only the Moon illumination variable was correlated with the NSB in both cases (-0.3 in rural areas and -0.35 in urban areas). The sky temperature showed a correlation with the NSB only in the urban area (-0.41). The indicated correlations are significant at the 0.01 level.

The results obtained in the urban area were confirmed by a second analysis using meteorological data provided by an independent entity (AEMET). The correlation of the sky temperature variable with the NSB was -0.3, compared to the -0.41 obtained initially. The variable illumination due to the Moon presence showed a correlation with the NSB of -0.48, compared to the -0.35 obtained initially. The rest of the variables showed a very low correlation with the NSB. The small differences between these values may be because the correlation between our meteorological data and those provided by AEMET is not perfect.

From these data, it can be concluded that the variables sky temperature and illumination due to the Moon will be relevant and influential in the observation. To optimise the conditions under which the observation will be carried out, the forecasts of these two variables should be consulted, looking for the lowest sky temperature and the moon phase closest to the new Moon (as the correlation in both cases is inverse).

A web application WeatherUEX [32] has been developed that allows real-time consultation of NSB and meteorological data for each area, which can help the sky observation in the studied area. The results obtained are intended for use by astronomers, astro-tourists and skywatchers, which may consult meteorological agencies for forecasts of the indicated variables, allowing them to know in advance whether the observation will be carried out under optimal conditions.

Limitations of the Study

It was impossible to compare the results obtained in the rural areas (Table 1) as the AEMET did not have the data record for these areas. The closest AEMET weather station to the study area was far away, so it was not possible to use these data. If these data had been available, a comparison of results could have been carried out, as was performed with the results obtained in the urban area. The equipment installed [26] did not allow the recording of the cloudiness variable, so we found an important limitation in this aspect. In future studies, it would be interesting to have specific equipment for recording this variable.

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Informed Consent Statement: Not applicable.

Data Availability Statement: The data supporting the reported results can be found at the following handle [31].

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Appendix A contains the information about the instruments used during the experiment.

The Sieltec Canarias SKYGLOW V3.1 photometer, (Figure A1), was used to measure the NSB in the different localities. Using WIFI or a mobile connection, the measurements are automatically stored on a server. The device is charged via the photovoltaic panel at the top. Below is a link to the manufacturer's website [25] and to an article detailing its technical characteristics [41].
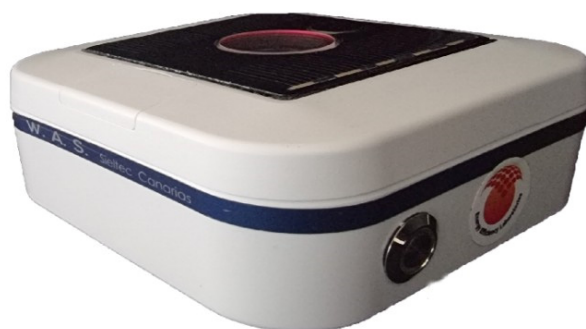
Figure A1. Sieltec Canarias SKYGLOW photometer.

The weather station used for the measurement of weather conditions was the Davis Vantage Vue + Weatherlink live (Figure A2). The information and technical specifications are detailed in the following link [26].

Figure A2. Davis Vantage Vue + Weatherlink live.

Appendix B

The coordinates and NSB level in the zone are detailed in Appendix B (Figures A3–A13). The photographs were taken by NASA's Blue Marble navigator [42].
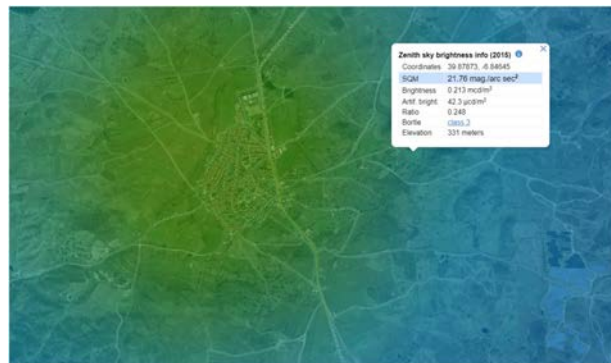
Figure A3. Coordinates and NSB in Zarza la Mayor.

Figure A4. Coordinates and NSB in Alcántara.

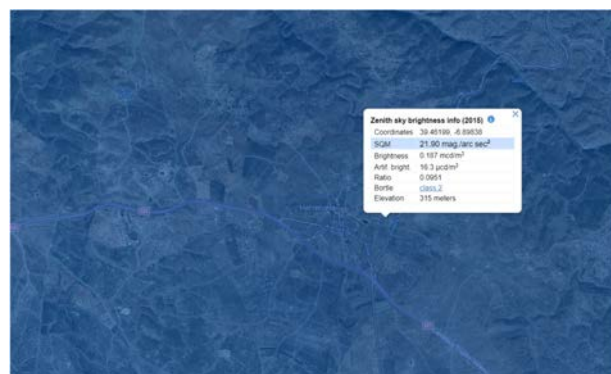**Figure A5.** Coordinates and NSB in Brozas.

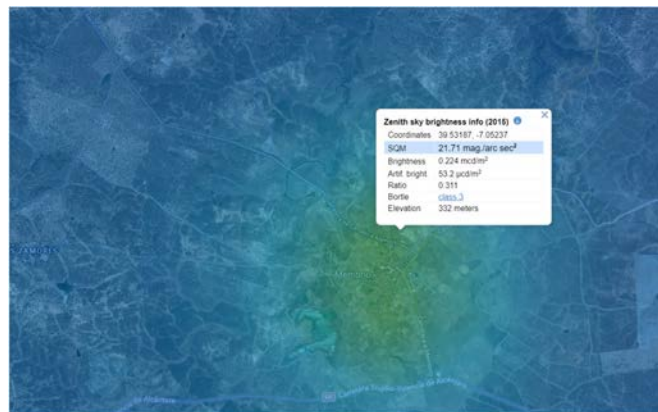**Figure A6.** Coordinates and NSB in Herreruela.

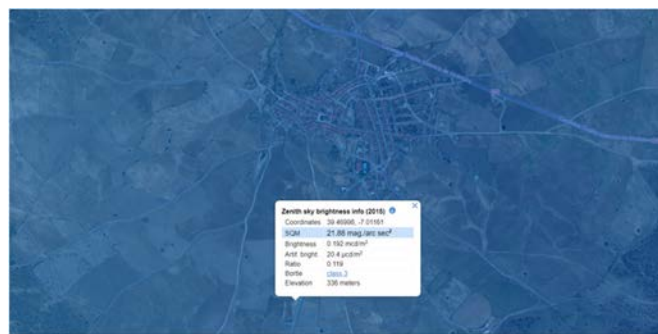**Figure A7.** Coordinates and NSB in Membrío.

Figure A8. Coordinates and NSB in Salorino.

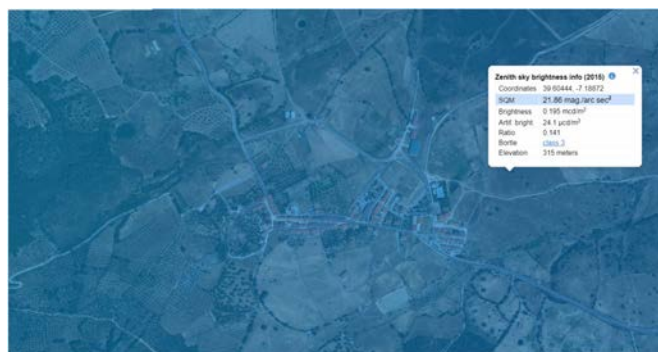**Figure A9.** Coordinates and NSB in Valencia de Alcántara.

Figure A10. Coordinates and NSB in Carbajo.

Figure A11. Coordinates and NSB in Santiago de Alcántara.

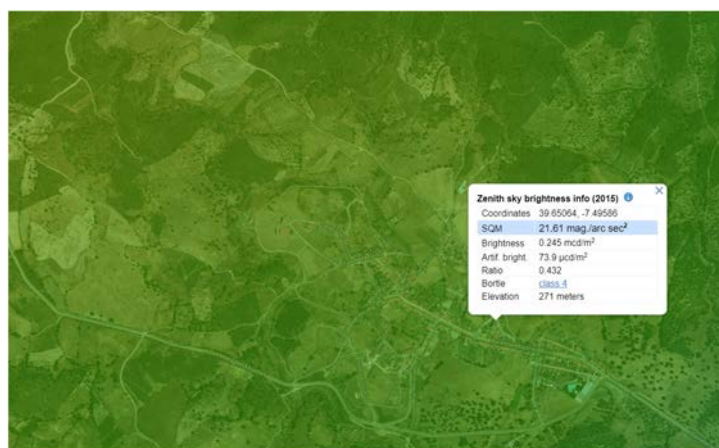**Figure A12.** Coordinates and NSB in Herrera de Alcántara.

Figure A13. Coordinates and NSB in Cedillo.

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