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Identifying distinct metrics for assessing night sky brightness

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ABSTRACT

Studying light pollution is an interest to researchers in a wide range of fields including astronomy, biology, civil engineering, ecology, and social science. Consequently, numerous sky brightness metrics have been developed over the years. However, what metrics are truly representative of the night sky quality and unique to the measured feature? The US National Park Service Night Skies Program has collected more than 1500 sets of night skies data throughout the United States. For each data set, a maximum of 56 metrics were measured through the combination of the captured images, Sky Quality Meter readings, and visual observations. This paper analyses these measurements and identifies a distinctive set of night sky brightness metrics based on the principal component analysis. Three major findings emerge. First, the commonly used metrics, such as the zenith brightness, horizontal illuminance, maximum vertical illuminance, all-sky light pollution ratio, Bortle class, and limiting magnitude, are highly correlated. Secondly, the observed sky brightness often offers a good estimate of the artificial light level despite the natural varying night sky background. Thirdly, a set of six metrics that consists of the zenith brightness and sky brightness percentiles are more distinctive when used to concisely describe night sky characteristics. These findings suggest that long-term night sky monitoring can be efficiently carried out by measuring the sky brightness percentiles on the observed all-sky images.

Key words: light pollution – methods: data analysis – techniques: photometric.

1 INTRODUCTION

Studying light pollution has became an interdisciplinary field of research. Artificially lit night sky impedes astronomical observations, disrupts wildlife's circadian rhythms, and degrades human experience of living under starry sky. To quantify the sky brightness, numerous metrics have been developed in different fields.

Zenith sky brightness is a widely measured characteristic of night skies. Zenith brightness is an important indicator of sky quality for astronomical observatories. At other places, the availability of an inexpensive Sky Quality Meter (SQM) has made measuring zenith brightness easily achievable by the general public (Pun & So 2012; Kyba et al. 2013). However, zenith brightness is an insensitive measure of light pollution, as the zenith is usually the last area of the sky affected by artificial light. Furthermore, tracking the zenith brightness may not be enough when considering the outdoor scenic values or ecological functions (e.g. Jechow et al. 2016, 2018).

These limitations motivated the diversification of methods and metrics for measuring night sky brightness (e.g. Hänel et al. 2018). For ecologists, illuminance levels are commonly used for studying how artificially lit environment affects animals and plants (Rich & Longcore 2013; Bennie et al. 2016). Ratios of the artificial light to the natural sky brightness were first introduced by Cinzano et al. (2000). And recently, all-sky light pollution ratio (ALR) arises as a favoured metric for measuring skyglow in both the ground-based observations (Duriscoe 2016) and satellite modelling (Duriscoe et al. 2018). Finally, visual assessments such as using the Bortle scale (Bortle 2001) and finding the limiting magnitude are often used by amateur observers and citizen scientists (Kyba et al. 2013).

This diversity of measurements raises questions about how to compare studies and metrics. Numerous studies have examined the correlations among a small set of metrics. Some compare the visual assessments to the measured sky brightness (e.g. Garstang 2000; Moore & Duriscoe 2015) while others try to determine the correlations among some commonly measured metrics (e.g. Duriscoe 2016). Although many studies relate different metrics to the zenith brightness, a comprehensive study is warranted to examine the full relationships among all these metrics.

In this paper, I use principal component analysis (PCA) to examine the relationships among metrics and identify a set of metrics to represent unique dimensions of night sky quality. Section 2 describes the data and analysis. The results in Section 3 show the relationships among the metrics along with the correlations between visual and SQM observations. In Sections 4 and 5, the study concludes by summarizing the major findings and interpreting the significance of this result in informing the development of long-term monitoring plans.

2 DATA AND ANALYSIS

2.1 Data source

The foundation for this study is the data collected by the US National Park Service (NPS) Night Skies Program. The team uses a commercial Nikon lens, a V-band filter, and a research-grade Charged Coupled Device (CCD; Duriscoe, Luginbuhl & Moore 2007) to capture high-resolution images of the entire sky. After basic reduc-

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tion, the images are subject to positional and absolute photometric calibrations. Next, a model of the natural sky is constructed based on the observing time and location (Duriscoe 2013). When the natural sky model is subtracted from the data, the residual light shows the skyglow caused by anthropogenic sources. In the end, each data set yields a pair of calibrated panoramic images, one showing the observed sky and the other showing the light only from anthropogenic sources.

The NPS Night Skies Program has been collecting data throughout the United States since the early 2000s. This effort resulted in thousands of night sky image data sets to date. Most of the observation sites do not have very bright skyglow. This study uses a suite of sky brightness metrics measured (Duriscoe 2016) for each image set.

In additional to capturing the sky images, the Night Skies team also collects visual assessment and SQM readings whenever possible. Visual assessment includes using the Bortle Scale and naked eye limiting magnitude. Bortle class is a nine-level numeric scale that measures the night sky's brightness based on visible sky objects. Limiting magnitude is the magnitude of the faintest star one can see with the naked eye. The hand-held SQM is aimed towards zenith when taking the measurement.

2.2 Data preparation

For each data set, 70 sky brightness measurements were automatically extracted from the captured images. Many of these numbers were representing the same metric but measured in different units. 53 unique metrics from each image set were left after removing the redundant entries. If visual assessment and SQM readings were recorded, three additional metrics (Bortle scale, naked eye limiting magnitude, and SQM) were also considered in the analysis.

The 53 calculated metrics are derived from both the image containing all light source and from the image containing only artificial light. These metrics include pixelwise sky brightness percentiles, illuminance values from the whole sky, illuminance from limited area of sky, sky surface brightness, ALR, and the percentage of visible stars. Each metric is described in detail in Appendix A.

Only data that pass through quality control are used in this study. A high-quality data set must not have bad image frames and must deemed usable during the data processing stage. Bad image frames, for example, include ruined images due to a car's headlight or images with inaccurate camera pointing. Among the thousands of data sets that were observed over 533 nights spread out through 360 sites across 126 NPS park units and 46 non-NPS locations, 1391 data sets passed the quality control and were used in this study. The results obtained in this paper are based on these selected samples taken by the NPS night skies team.

2.3 Principal component analysis

PCA is a statistical method that transforms possibly correlated variables into a set of linearly independent variables called principal components. The principal components are ranked by the amount of variance each component can capture, and all the principal components are orthogonal to each other, forming an uncorrelated basis set. In a highly correlated set of variables, PCA can be used to reduce the dimensionality of the work space by using a lower dimension set of principal components to describe the data. All the data processing was done in PYTHON with the use of scikit-learn (Pedregosa et al. 2011) for doing the standardized PCA.

This study uses PCA to examine the relationships among different metrics and identify the latent dimensions. The input data are in a matrix of 53 metrics × 1391 data sets. The data sets were scaled to the mean of 0 and standard deviation of 1. A PYTHON PCA object was then fit to the data. After the PCA process, the 1391 dimensions (or data sets) were collapsed into a few principal components. Then, the 53 metrics were projected on to the first two principal components.

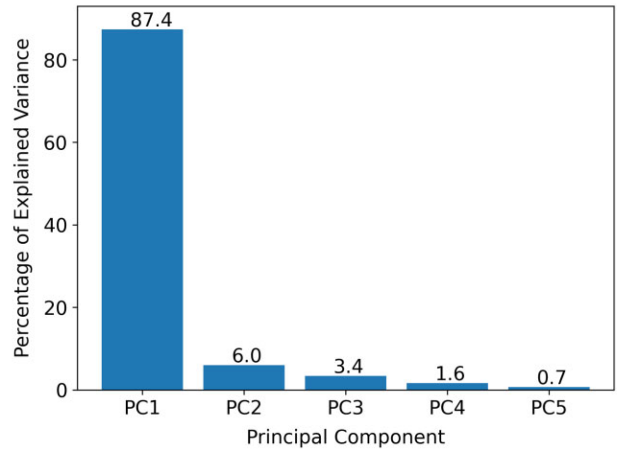

Figure 1. Scree plot showing the percentage of explained variance for the first five principal components. Only five principal components are needed to explain 99 per cent of variations among the metrics.

3 RESULTS

3.1 Relationships among the metrics

PCA successfully captures most of the variance with just a handful of principal components. After PCA is applied to the original matrix of 53 metrics × 1391 data sets, the new matrix reduces its dimension to 53 metrics × 5 principal components. Using only five principal components is enough to explain 99 per cent of the variance among the 53 metrics. Fig. 1 shows the scree plot describing how the percentage of explained variance is distributed across the first five principal components. The 1st principal component accounts for 87 per cent of the variance across all metrics. Subsequent principal components account for approximately half of the remaining variance, which is significantly less compared to the variance accounted by the 1st principal component.

Projecting the metrics on the first two principal components reveals the metrics' uniqueness. If two metrics are similar, they are likely to locate close to each other in this PC1-PC2 space. Fig. 2 shows the 53 metrics plotted against the first two principal components. After examining the location of each metric, two observations are noted. First, most of the metrics are clustered towards the middle left-hand side. This clustered distribution means many metrics are similar to each other. Secondly, metrics derived from the image containing all light sources separate along the second principal component from the metrics derived from the image containing only artificial light. This finding is highlighted by the red (artificial light) and grey (all light) colours in Fig. 2.

Many commonly used metrics are closely related the each other. Some of these metrics include horizontal and maximum vertical illuminance, visible star counts, average sky brightness, zenith sky brightness, and ALR. These metrics are clustered in the tiny cyan box shown in Fig. 2. Based on their projected proximity, these metrics are measuring related characteristics of the night sky quality. Fig. 3 shows the zoomed-in view of the cyan box. In this crowded space,

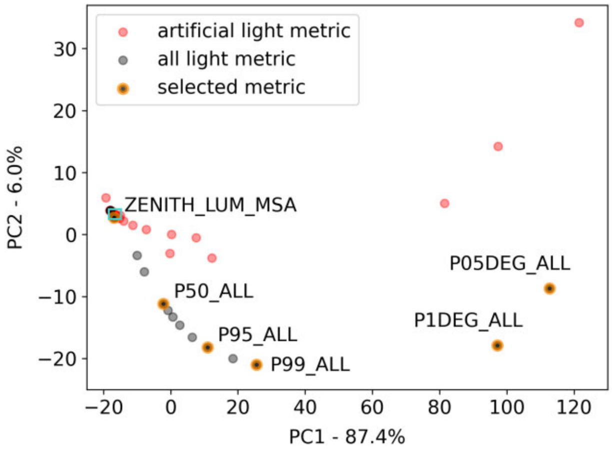

Figure 2. Metrics projected on to the first two principal components. Metrics derived from images containing only artificial light (red points) appear to separate along the second principal component from the ones derived from images containing all light (grey points). The commonly used metrics are all clustered in the cyan box (zoomed-in view shown in Fig. 3). Yellow-edged points are selected for forming a concise set of metrics proposed in this paper.

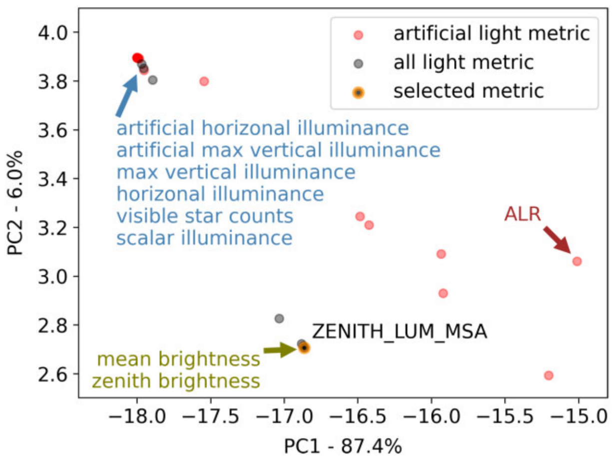

Figure 3. Distribution of the commonly used metrics projected on to the first two principal components. This figure is the zoomed-in view of the cyan box shown in Fig. 2. All these commonly used metrics are closely related to each other and can be subdivided into three groups: (i) illuminance measurements and the number of visible stars, (ii) average sky brightness and zenith sky brightness, and (iii) ALR.

the commonly used metrics can be subdivided into three groups: (i) illuminance measurements and the number of visible stars, (ii) average sky brightness and zenith sky brightness, and (iii) ALR.

Brightness percentiles are more distinctive metrics for describing night sky characteristics. Opposite to forming a cluster, metrics that are more unique to each other tend to be farther apart in the PC1-PC2 space. Therefore, the key to identify a unique metric set is to select ones spread out in Fig. 2, especially along the 1st principal component that captured the most amount of variance. One other aspect to consider when selecting the metrics is the complexity associated in obtaining them. Compared to the artificial light metrics, the metrics derived from the images containing all light sources are much easier to obtain because there is no need for doing natural sky modelling and subtraction. With the consideration of selecting points across the 1st principal component and the preference of choosing simpler metrics, the results of the analysis suggest using a concise

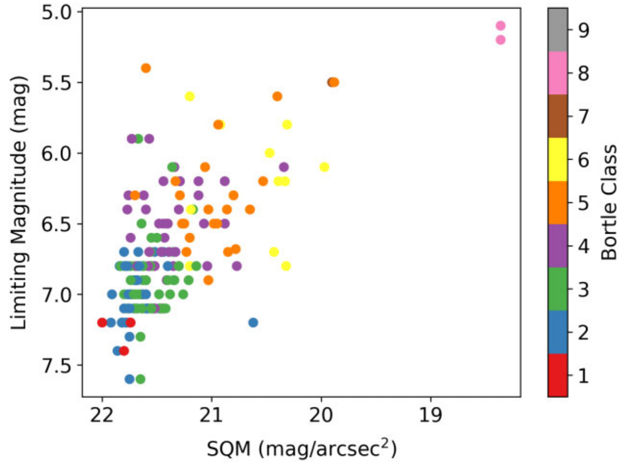

Figure 4. Relationship between the limiting magnitude, SQM, and Bortle class. There are 176 data entries where all three measurements were made. The limiting magnitude, SQM, and Bortle class measurements are correlated with the correlation coefficients listed in Table 1.

Table 1. Correlation coefficients between limiting magnitude, Bortle scale, and SQM measurements.

	Limiting magnitude	Bortle class	SQM
Limiting magnitude	1	−0.75	0.67
Bortle class	−0.75	1	−0.76
SQM	0.67	−0.76	1

set of metrics (yellow-edged points in Fig. 2), derived from images containing all light sources, consists of the zenith brightness, 50th, 95th, 99th, 99.995th (brightest square degree), and 99.999th (brightest 0.25 square degree) percentiles to adequately describe the night sky characteristics.

3.2 SQM and visual observations

SQM measurements and visual assessments are correlated with each other. In addition to the images, 176 nights have three additional measurements taken: limiting magnitude, Bortle scale, and SQM. These data points are plotted in Fig. 4. These measurements are considered separately from the previous analysis because they are measured independently from the images of the night skies. Table 1 lists the correlation coefficients between limiting magnitude, Bortle scale, and SQM measurements. These three metrics show moderate to strong relationships among each other.

3.3 Estimating sky brightness metrics

In cases where measurements are limited, some commonly used metrics that have physical or ecological significance can be estimated. As inferred in Figs 2 and 3, zenith brightness can serve as a good estimator for horizontal illuminance, maximum vertical illuminance, average sky brightness, and ALR based on their close proximity on the PC space. Fig. 5 shows the relationships between the zenith brightness and some metrics that are commonly used in other physical or ecological studies based on the 1391 data sets used in this study. For zenith brightness of about 21.2 and darker, zenith brightness is not a sensitive estimator for small amount of horizontal illuminance, max vertical illuminance, and ALR. For sites with zenith brighter

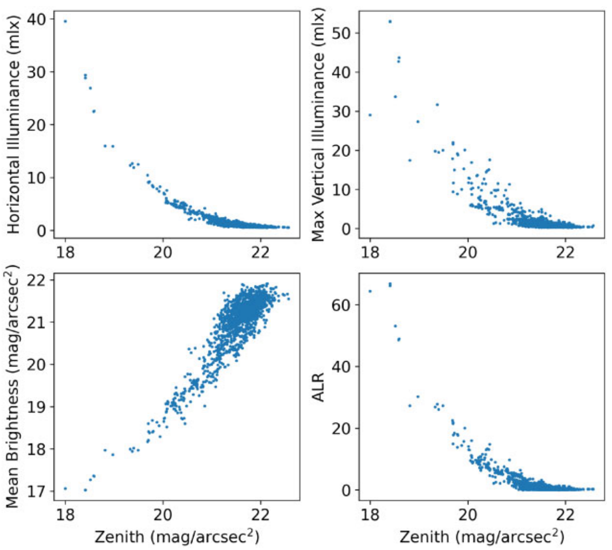

Figure 5. Relationships between commonly used metrics in physical or ecological studies and the zenith brightness. Horizontal illuminance, maximum vertical illuminance, average sky brightness, and ALR are plotted against the zenith brightness. In general, in cases where only zenith brightness were measured, scatter plots like these can be useful for estimating the metrics with physical or ecological significance.

than 21.2, the correlated relationships between zenith brightness and horizontal illuminance, max vertical illuminance, and ALR become more apparent.

4 DISCUSSION

Considering how the metrics are calculated, it is not surprising that the commonly used metrics are related to each other. These related metrics often derived from the similar area of the sky. Specifically, horizontal illuminance, scalar illuminance, visible star counts, mean sky brightness, and ALR all take the brightness over the whole sky into account. Moreover, zenith brightness and horizontal illuminance are both heavily influenced by the brightness overhead. Vertical illuminance is calculated based on the brightness from half of the sky. There is a substantial overlap on the sky area where these metrics are derived. This wide overlap can explain why the PCA result shows the commonly used metrics are closely related to each other.

The six suggested metrics are more distinct because they form an image brightness summary profile and are derived from different parts of the sky. The six selected metrics are the zenith brightness, 50th, 95th, 99th, 99.995th, and 99.999th percentiles. As zenith is usually the darkest area of the sky, the zenith measurement is equivalent to a low brightness percentile. In other words, these six metrics are essentially all percentile measurements. Percentiles are natural candidates for preserving most of the 2D information in 1D space. In this case, percentiles provide a 1D summary of the image. Additionally, percentile calculation avoids using overlapped sky area. Considering these two facts, it is not surprising why the PCA identifies percentiles as more independent metrics.

SQM measurements and the visual assessments do not provide unique information on sky quality in addition to the six suggested metrics. Because SQMs are pointed towards zenith, the measurements are directly affected by the zenith brightness. Bortle scale and limiting magnitude are correlated with SQM measurements as shown in Table 1. Note that the data explored here contain a wide range of sky brightness. The correlation might be poorer when limiting the data to ALR<3, and Bortle Class 1–5 are less distinguishable with zenith brightness measurements alone (Moore & Duriscoe 2015). On a gross scale, limiting magnitude, Bortle scale, and SQM measurements can all be represented by measuring the zenith brightness. Note that visual observations such as limiting magnitude and Bortle scale are inherently more uncertain because of human error. Thus, although many metrics are related, selecting the objectively measured zenith brightness as the representative metric is preferred.

This study focuses on examining the relationships among metrics, not proposing universal metrics to use for all fields of study. Indeed, what metrics to use are often best determined by the objective of the study. Studies focused on astronomical observations, ecological effects, visitor experience, and skyglow modelling might naturally choose different metrics. And it is always better to calculate or measure the metrics directly instead of obtaining them through modelling or correlations. The six suggested metrics represent unique dimensions of night sky quality and are better suited for studies focusing on using non-redundant metrics for monitoring the night sky brightness.

Other metrics not investigated in this study, such as spectral measurements, could provide additional characterization of the night sky quality. Outdoor lighting technology is evolving, with LEDs becoming more popular because of improved energy efficiency, better control, and lower maintenance costs. However, retrofitting outdoor lights to LEDs often changes the appearance of skyglow (e.g. Hung et al. 2021). Spectral measurements are therefore becoming an increasingly important aspect for characterizing skyglow. This study only focuses on the relationship between the photometric metrics. Due to the lack of available data, this study does not investigate the relationship between multiwavelength or spectral measurements of the skyglow. Once the multiwavelength data become more abundant, future research using the similar PCA analysis could reveal additional unique metrics for characterizing the night sky quality.

5 CONCLUSIONS

This data-driven analysis reveals two important relationships: (1) The commonly used metrics, such as the horizontal illuminance, maximum vertical illuminance, visible star counts, average sky brightness, zenith sky brightness, and ALR, are closely related to each other. They track similar brightness characteristics of the night sky. (2) Brightness percentiles, on the contrary, are more unique metrics. These selected metrics consists of the zenith brightness, 50th, 95th, 99th, 99.995th (brightest square degree), and 99.999th (brightest quarter square degree) percentiles. They form a concise metric set suitable for summarizing brightness over the whole sky.

Long-term monitoring needs to record sky brightness both at zenith and near horizon. The six distinctive metrics suggest that the sky brightness percentile profile is often unique from place to place. The uniqueness in brightness profiles also means that the zenith is insensitive to bright lights near the horizon. Therefore, to fully characterize the entire night sky condition, monitoring zenith and near horizon are both necessary.

Taking all-sky images is the most effective way for long-term monitoring. The PCA result shows that the observed sky brightness is often a good estimate of the artificial light level despite the natural varying night sky background based on the statistical analysis. For any specific site, especially a dark site, a more detailed analysis should be carried out to monitor the exact level of artificial light over the whole sky. In general, if all-sky images are available, all metrics can be easily calculated. The six selected metrics do not require natural sky subtraction, which greatly simplifies the data processing requirement. In summary, simply capturing all-sky images is a versatile way for effective long-term monitoring.

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DATA AVAILABILITY

The data underlying this article were collected by US National Park Service Natural Sounds and Night Skies Division (www.nps.gov/nsnsd). The derived data generated in this research will be shared on reasonable request to the corresponding author.

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APPENDIX A: METRICS DERIVED FROM THE IMAGES

The 53 calculated metrics are derived from each image data set. The nomenclature used in naming the metrics follows the rules below. P stands for the percentile for brightness. The notation immediately following P indicates the percentage of the pixels darker than the value of the metric. ALL means all light sources were considered whereas ART means natural sky brightness has been subtracted so only artificial light is measured. MLX denotes the unit of millilux. VERT is the short hand of vertical illuminance, and HORIZ is horizontal illuminance. MCCD is microcandela per square meter. LUM stands for luminance. The ALR can be calculated by dividing the metric (31) MEANLUM_ART_MCCD by 248.2818 microcandela per square meter. ZA70, ZA80, and ZA54 metrics are only considering the area of the sky within the zenith angle of 70°, 80°, and 54° correspondingly. COS indicates that the pixel values are multiplied by the cosine of the incident angle. MSA is shorthanded for magnitude per square arcsec.

(i) P05DEG_ALL: 99.999th brightness percentile in the observed sky. The aggregated area of pixels brighter than this value is roughly 0.25 square degree (0.5 deg × 0.5 deg).

(ii) P1DEG_ALL: 99.995th brightness percentile in the observed sky. The aggregated area of pixels brighter than this value is roughly 1 square degree.

(iii) P99_ALL: 99th brightness percentile in the observed sky.

(iv) P98_ALL: 98th brightness percentile in the observed sky.

(v) P95_ALL: 95th brightness percentile in the observed sky.

(vi) P90_ALL: 90th brightness percentile in the observed sky.

(vii) P80_ALL: 80th brightness percentile in the observed sky.

(viii) P70_ALL: 70th brightness percentile in the observed sky.

(ix) P60_ALL: 60th brightness percentile in the observed sky.

(x) P50_ALL: 50th brightness percentile in the observed sky.

(xi) P01_ALL: 1st brightness percentile in the observed sky.

(xii) P0005_ALL: 0.05th brightness percentile in the observed sky.

(xiii) P05DEG_ART: 99.999th brightness percentile of the artificial light. The aggregated area of pixels brighter than this value is roughly 0.25 square degrees (0.5 deg × 0.5 deg).

(xiv) P1DEG_ART: 99.995th brightness percentile of the artificial light. The aggregated area of pixels brighter than this value is roughly 1 square degrees.

(xv) P99_ART: 99th brightness percentile of the artificial light.

(xvi) P98_ART: 98th brightness percentile of the artificial light.

(xvii) P95_ART: 95th brightness percentile of the artificial light.

(xviii) P90_ART: 90th brightness percentile of the artificial light.

(xix) P80_ART: 80th brightness percentile of the artificial light.

(xx) P70_ART: 70th brightness percentile of the artificial light.

(xxi) P60_ART: 60th brightness percentile of the artificial light.

(xxii) P50_ART: 50th brightness percentile of the artificial light.

(xxiii) P01_ART: 1st brightness percentile of the artificial light.

(xxiv) ALLSKY_ART_MLX: Scalar illuminance of all artificial light sources in the sky in millilux.

(xxv) MAXVERT_ART_MLX: Maximum vertical illuminance from artificial light sources in millilux.

(xxvi) MEANVERT_ART_MLX: Mean vertical illuminance from artificial light sources in millilux.

(xxvii) MINVERT_ART_MLX: Minimum vertical illuminance from artificial light sources in millilux.

(xxviii) HORIZ_ART_MLX: Horizontal illuminance from artificial light sources in millilux.

(xxix) BRIGHTEST_ART_MCCD: Brightest sky luminance containing only artificial light measured in microcandela per square meter.

(xxx) ZENITH_LUM_ART_MCCD: Zenith brightness containing only artificial light measured in microcandela per square meter.

(xxxi) MEANLUM_ART_MCCD: Mean sky luminance containing only artificial light measured in microcandela per square meter. The ALR can be calculated by dividing this value by the reference natural sky brightness of 248.2818 microcandela per square meter.

(xxxii) ZA70_ART_MLX: Illuminance in millilux of all artificial light sources within 70° zenith angle.

(xxxiii) ZA70_MAXVERT_ART_MLX: Maximum vertical illuminance in millilux from artificial light sources within 70° zenith angle.

(xxxiv) ZA70_MEANVERT_ART_MLX: Mean vertical illuminance in millilux from artificial light sources within 70° zenith angle.

(xxxv) ZA70_MINVERT_ART_MLX: Minimum vertical illuminance in millilux from artificial light sources within 70° zenith angle.

(xxxvi) ZA70_HORIZ_ART_MLX: Horizontal illuminance in millilux from artificial light sources within 70° zenith angle.

(xxxvii) ZA70_BRIGHTEST_ART_MCCD: Brightest sky luminance containing only artificial light measured in microcandela per square meter within 70° zenith angle.

(xxxviii) ZA70_MEANLUM_ART_MCCD: Mean sky luminance containing only artificial light measured in microcandela per square meter within 70° zenith angle.

(xxxix) ZA80_ART_MLX: Illuminance in millilux of all artificial light sources within 80° zenith angle.

(xl) ZA80_MAXVERT_ART_MLX: Maximum vertical illuminance in millilux from artificial light sources within 80° zenith angle.

(xli) ZA80_MEANVERT_ART_MLX: Mean vertical illuminance in millilux from artificial light sources within 80° zenith angle.

(xlii) ZA80_MINVERT_ART_MLX: Minimum vertical illuminance in millilux from artificial light sources within 80° zenith angle.

(xliii) ZA80_HORIZ_ART_MLX: Horizontal illuminance in millilux from artificial light sources within 80° zenith angle.

(xliv) ZA80_BRIGHTEST_ART_MCCD: Brightest sky luminance containing only artificial light measured in microcandela per square meter within 80° zenith angle.

(xlv) ZA80_MEANLUM_ART_MCCD: Mean sky luminance containing only artificial light measured in microcandela per square meter within 80° zenith angle.

(xlvi) ZA54_COSLUM_MSA: Sky luminance calculated with pixels within 54° zenith angle. Each pixel value is multiplied by the cosine of the incident angle and weighted by the sustained area of sky.

(xlvii) AVE_LUM_MSA: Average sky brightness containing all light sources measured in magnitude per square arcsec.

(xlviii) ZENITH_LUM_MSA: Zenith sky brightness containing all light sources measured in magnitude per square arcsec. This is calculated using the median pixel value within the 20-pixel-radius aperture centred at the zenith. The plate scale is $1^{\prime}.4$/pix for most of the NPS systems currently in use.

(xlix) BRIGHTEST_LUM_MSA: Brightness sky luminance containing all light sources measured in magnitude per square arcsec.

(l) ALLSKY_MLX: Scalar illuminance considering all light sources in the sky in millilux.

(li) HORIZ_MLX: Horizontal illuminance from all light sources in the sky in millilux.

(lii) MAXVERT_MLX: Maximum vertical illuminance from all light sources in the sky in millilux.

(liii) VISSTARS_RATIO: Ratio of the number of stars visible under skyglow to the number of stars visible under the natural sky.

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