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Communication

„Skywatcher" system for daylight measurements

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Abstract: The purpose of this work is to determine the possibility of using an automated Sky-Watcher Virtuoso system to analyze distribution of sky luminance. The article presents the procedure for measuring the sky luminance distribution defined according to CIE using a manual luminance meter cooperating with the SkyWatcher system. The use of matrix luminance meter was also analyzed.

Keywords: daylight, luminance, measurement system, sky luminance, lighting applications, optical metrology

1. Introduction

Daylight has a large impact on human functioning (Human Centric Lighting) by setting, for example, circadian rhythm, mood, and thus general mental and physical health. The yardstick for determining lighting in a room is the illuminance. The illuminance mainly depends on the sun movement during the day and the permeability and thickness of the cloud layer. [1-12]

This article analyzes the possibility of measuring the sky luminance distribution using the SkyWatcher Virtuoso automated system, which was originally used for astronomical observations. However, it has the ability to mount other measuring devices and can be manually controlled or programmed according to the assumed algorithm. In order to correctly luminance distribution maps, it is necessary to make reference measurements using a matrix meter and a typical point luminancemeter. Based on the sky luminance maps, it is possible to segment the celestial sphere into sub-areas with an average luminance value based on the Tregenza division [13-16]

2. Sky luminance calculation

The standardization of sky luminance distributions is based on 15 models according to CIE [17], which describe atmospheric phenomena (cloud configurations) closely related to luminance distributions. The distribution of daylight illumination on any working plane is calculated numerically. The sky models developed, with luminance distributions determined for them in the zenith of the LVZ sky, reflect the state of the sky for individual degrees of cloudiness and diffusion of particles in the atmosphere. [18-30]

According to the calculation procedure proposed by the CIE [17], geographical coordinates and time zone in the examined location are determined, and then the position of the Sun in the sky on a given day and at a specific time is determined. The declination angle δ, which determines the angular position of the blue equator relative to the ecliptic, is related to the next day in year n:

$$\delta = 23,45^{o} \sin\left(360 \ \frac{284+n}{365}\right) \tag{1}$$

The luminance of any element is determined by the horizontal angle γ_s of the position the center of solar disk, calculated by the relationship:

$$\sin\gamma_s = \sin\delta\sin\phi + \cos\delta\cos\phi\cos\omega \quad (2)$$

The illuminance when the sun zenith is calculated from the following relation:

$$E_{VO,\varepsilon} = 133,8\varepsilon = 133,8\left[1 + 0,034\cos\left(\frac{2\pi}{365}(n-2)\right)\right] \quad (3)$$

and the illuminance on a horizontal surface in an open area on a given day is determined by the formula:

$$E_{VOh} = E_{VO}\cdot\delta\cdot\sin\gamma_s \quad (4)$$

Then, based on the relationship between the sky luminance at the calculation point L_{vz} divided by the horizontal illuminance of daylight E_{vd}, the sky model is selected.

$$\frac{L_a}{L_{VZ}} = \frac{1 + a\cdot\exp\left(\frac{b}{\sin\ \gamma_s}\right)}{1 + a\cdot\exp(b)} \quad (5)$$

Where: a and b - coefficients characteristic for a given model of the sky developed by CIE, L_a - is the luminance of the sky at a specified azimuth in relation to the luminance of the Sun zenith L_{VZ}, γ_s - maximum horizontal angle.

The solar luminance at the zenith is calculated in this case from dependence:

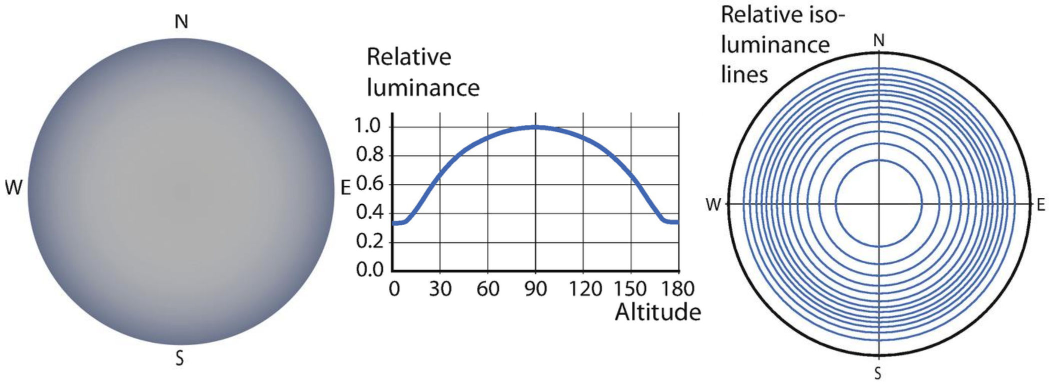
$$L_{VZ} = B\frac{E_{Vd}}{E_{Voh}}\cdot\sin\gamma_s \quad (6)$$

Based on the above relationships (formulas 5 and 6), it is possible to calculate the sky luminance La. Unfortunately in real conditions it is difficult to unequivocally choose the correct CIE luminance distribution model. Therefore measurements of the luminance distribution should be made according to the Tregenza methodology [31]. Obtained luminance maps are needed to model energy efficiency in buildings (lighting and air conditioning control) and are used to determine production indicators (Performance Ratio) in photovoltaic systems.

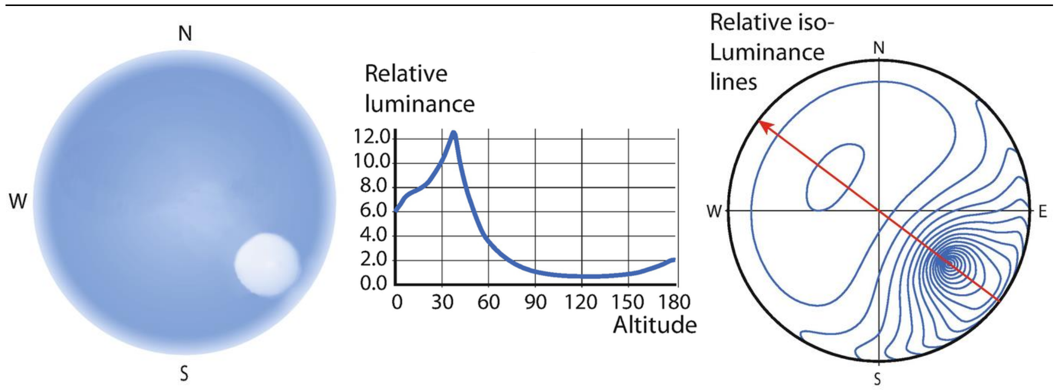
Table 1 shows three selected characteristic sky models used in further analyzes. The first column shows daylight luminance distribution in the axial section. The second column shows the same daylight luminance distribution but in a polar system. The third column presents photographs of real sky corresponding to a given situation. For each of the sky models, the characteristic values of the luminance distribution were determined, i.e. the ratio of the horizontal illuminance of daylight to the horizontal illuminance, taking into account the height of the Sun.

Table 1. Selected sky luminance models in accordance to CIE [17, 37]

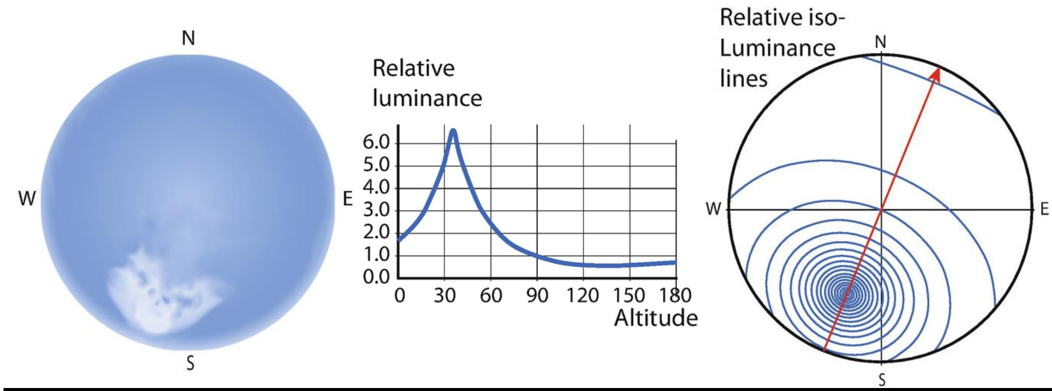
CIE Standard Overcast Sky



CIE Standard Clear Sky



CIE Partly Cloudly Sky



3. Measurement methodology

Measurements of luminance distribution are usually performed using point luminancemeter which, unlike matrix luminancemeter, are characterized by more accurate V(λ) spectral correction. It was achieved by using dedicated optical filters placed on the surface of a single silicon detector used in the point luminance meter - Figure 1.

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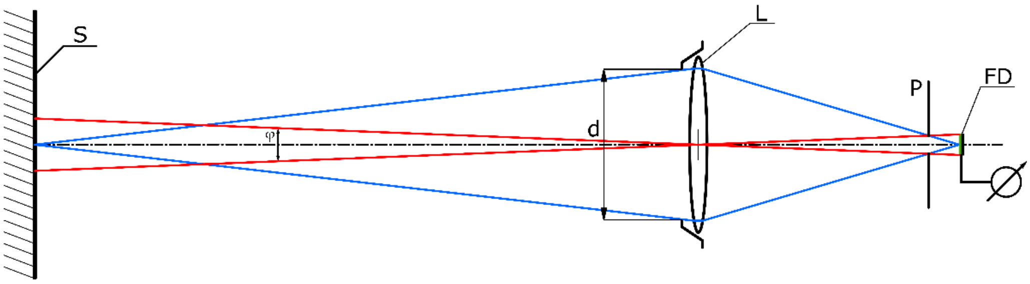

Figure 1. Simplified optical system of the single-point luminance meter: S - examined surface, φ - observation angle, d - diameter of the entrance shutter, L - optical system, P – detector shutter, FD - a single photodetector with a set of optical filters.

Construction of modern single-point luminance meters allows the use of a single set of optical filters. Performing such operation, the relative spectral sensitivity of the silicon photodiode can be adapted to the relative spectral sensitivity of the human eye $V(\lambda)$. the idea of such an operation is shown in Figure 2.

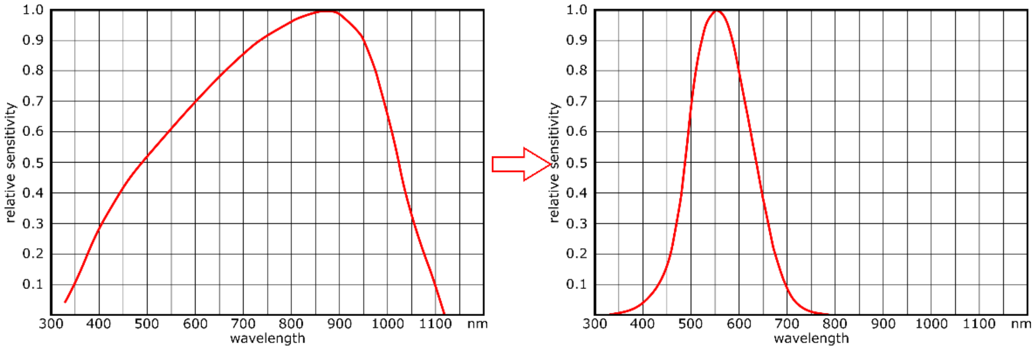

Figure 2. Comparing the relative sensitivity of the silicon detector and the relative sensitivity of the human eye $V(\lambda)$.

When the analysis of the luminance distribution covers a larger area, measuring with a conventional luminance meter can be extremely laborious. It is caused by the necessity to direct the measuring field of the luminance meter point-by-point to the analyzed sections of the tested surface - Figure 3.

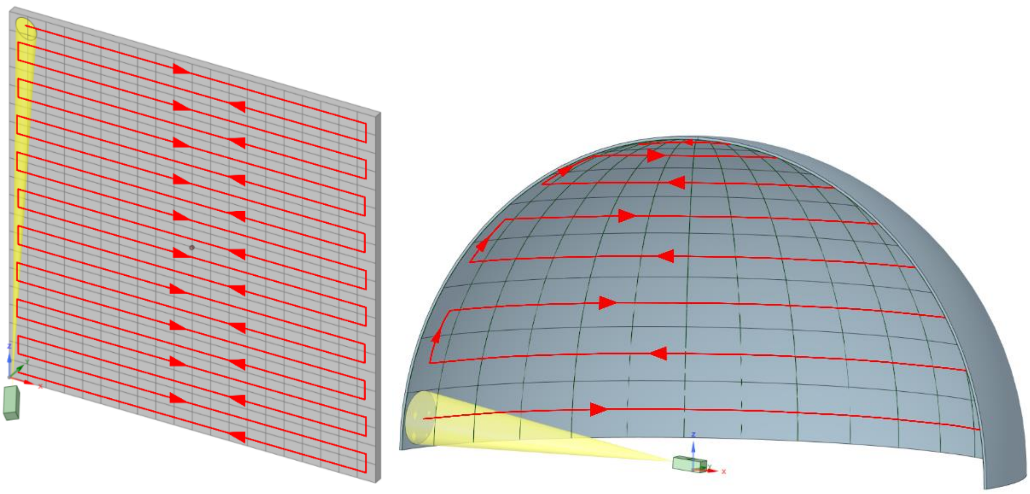

Figure 3. Large surface luminance measurement made with a conventional single point luminance meter.

In order for the measurements of larger areas to be efficient and their results as close to the real values as possible, additional equipment should be added to the stand. For example manual or automated tripods greatly facilitate and speed up the measurements.

The solution proposed by the authors is the use of an automatic photo head with Sky-Watcher Virtuoso electric drive, connected successively with a manual LS100 luminancemeter and a LMK Mobile Air matrix luminancemeter [31].

Taking luminance measurements with generally available meters is currently extremely laborious. In the case of point luminance meters, it is necessary to precisely aim the meas-uring head towards the analyzed point. Due to the high concentration of measurement points and the need for subsequent analysis of individual areas, more people who per-form measurements decide to use matrix meters. In this case, a photo is analyzed and an appropriate measurement grid is placed on top of it. Dedicated computer programs allow you to quickly calculate a large number of measurement points and automatically analyze the data obtained from measurements.

However, point luminance meters outperform matrix meters in another respect. They are characterized by a more precise spectral correction of V (λ) and maintain the conditions of the measurement geometry, without the distortion effects characteristic of matrix meters. Therefore, the authors of this article propose to expand the measuring station and use the LS100 point luminance meter in conjunction with the SkyWatcher Virtuoso automatic photo head with electric drive, in order to improve the measurements. For comparison and better verification of the measurement results, the analysis was also carried out for the LMK Mobile Air matrix meter. The measuring station was additionally equipped with the SkyWatcher SynScan remote control, which enables programming and constant monitor-ing of the position of the tested objects.

The SkyWatcher Virtuoso device (Figure 4) is an extensive and feature-rich photo tripod that allows you to take time-lapse movies, photograph selected objects in the right order and at set intervals, and the device also allows you to photograph a 360 ° sphere.

Figure 4. Sky Watcher Virtuoso photo head

The device is equipped with two bipolar stepper motors which propel the worm gear and enable the head to move in the vertical and horizontal axis. Due to the lack of reduction gears, backlash was reduced, which resulted in high accuracy of the head positioning. This solution has been patented by Sky Watcher as Freedom Find ™ [12] and is used in all heads made by this company. It allows the head to be moved in both axes (Figure 5) either manually, by releasing the clutch, or electronically, without losing its current position.

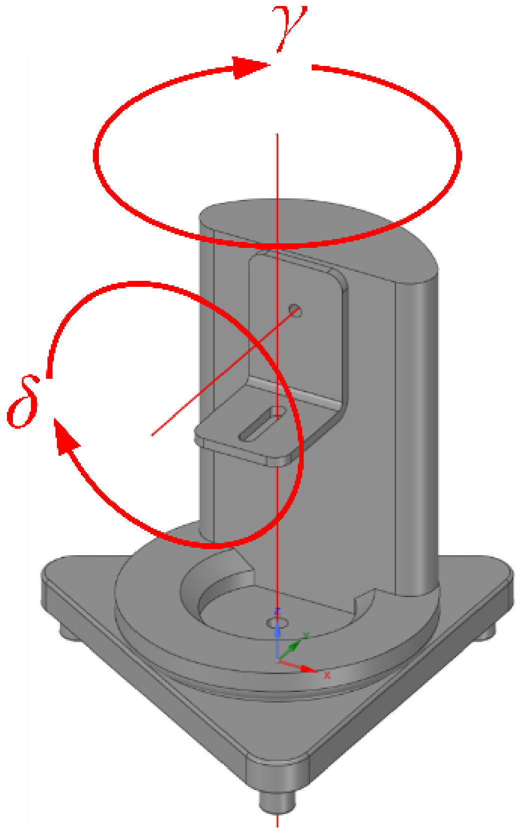

Figure 5. Declination angle δ and horizontal angle γ compared with SkyWatcher Virtuoso axes.

The manufacturer does not publish data on the accuracy of the Virtuoso head positioning. Comparing their other heads which use the same technology, it occurred that the positioning accuracy of the EQ8 head is approximately 0.12 arc seconds [31], which corresponds to the displacement of the measuring point by ± 6mm from a distance of 10m.

The measurements of the measuring head positioning accuracy have been published in the literature [31]. The stand, shown in Figure 6, consisted of Sky Watcher Virtuoso head, SynScan remote control and Mitutoyo time sensor with a measuring range of 1 mm and an accuracy of 0.01 mm placed on a magnetic base.

The difference from the base position was 0.05-0.07 mm. The results of the head positioning accuracy were satisfactory and qualified it for further work related to luminance measurements.

Additionally SkyWatcher is very mobile. The lightweight tripod is powered by eight AA batteries, so it can be used anywhere, without being limited by the proximity of an electrical socket. SkyWatcher Virtuoso has a handle that can be controlled manually in two planes (vertical and horizontal), or programmed in such a way that it moves smoothly between 20 programmable angular positions of the head and takes photos in timelapse mode. The speed of the head can be selected from five available variants [12]:

– speed 1: 360° rotation within 24 hours,
– speed 2: 360° rotation within 6 hours,
– speed 3: 360° rotation within 3 hours,
– speed 4: about 1.2 ° per second,
– speed 5: about 1.2 ° per second.

The first three speed options are primarily used for time-lapse imaging, while speed options four and five are recommended for standard videography.

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Figure 6. Stand for measuring the repeatability of Skywatcher settings

Figure 7. Luminancemeters - matrix and conentional (point measure)

The Skywatcher system has been linked to the matrix image recording with a digital camera, making it possible to develop a stand for measuring sky luminance distribution.

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The test stand is equipped with two devices for concurrent recording of luminance distribution.

The Canon 5D Mark II digital camera with a fisheye lens captured the sky image. The obtained image in RAW format was processed using MatLab software with “Image Processing And Computer Vison” library. After converting color image into a grayscale image, average pixel value was read from the image from an area of 9pix x 6pix, which is consistent to the measurement field of the Minolta LS-110 meter (1/3°). The transformation function for exposure parameters f / 5.6, 1 / 500s, ISO 200 as shown in Fig. 8 was obtained. On this basis, the "pixel value" was converted into registered part of sky luminance.

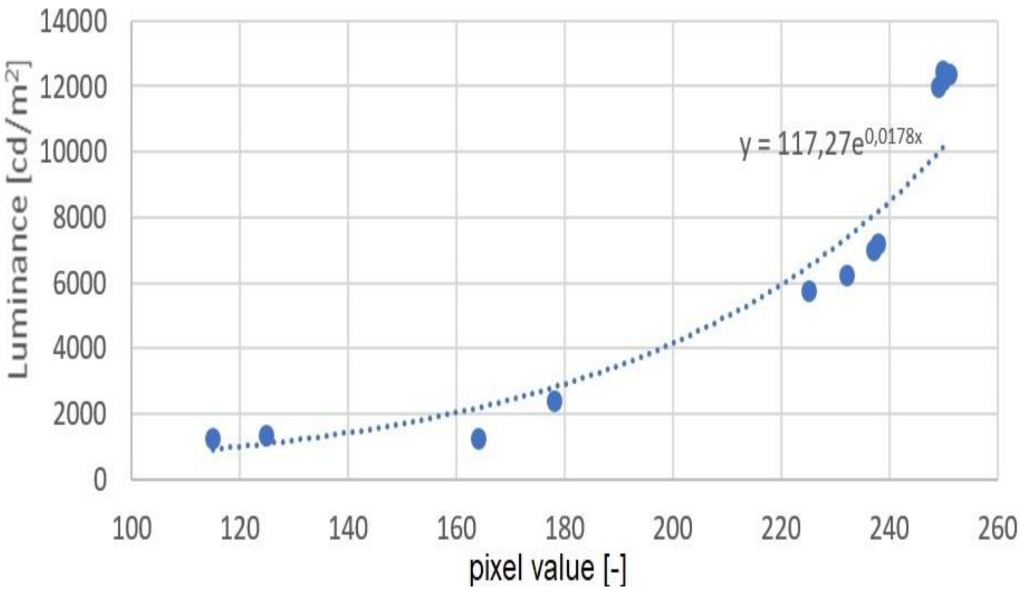

Figure 8. Luminance in the "pixel value" function

4. Measurements

The Skywatcher Virtuoso system, with mounted luminancemeters, allowed the determination of sky luminance distributions. The measurements consisted in determining a reference map using a matrix meter, and then comparing it with the luminance distribution made using a point luminancemeter. This procedure is necessary because matrix meters require calibration each time, but they read the total sky luminance distribution in an instant. Point meters do not have to be calibrated but to determine the luminance distribution it is necessary to point the meter laboriously at a specific point in the sky. According to the Tregenza measurement model, 145 points distributed over the sky hemisphere are required (Fig. 9).

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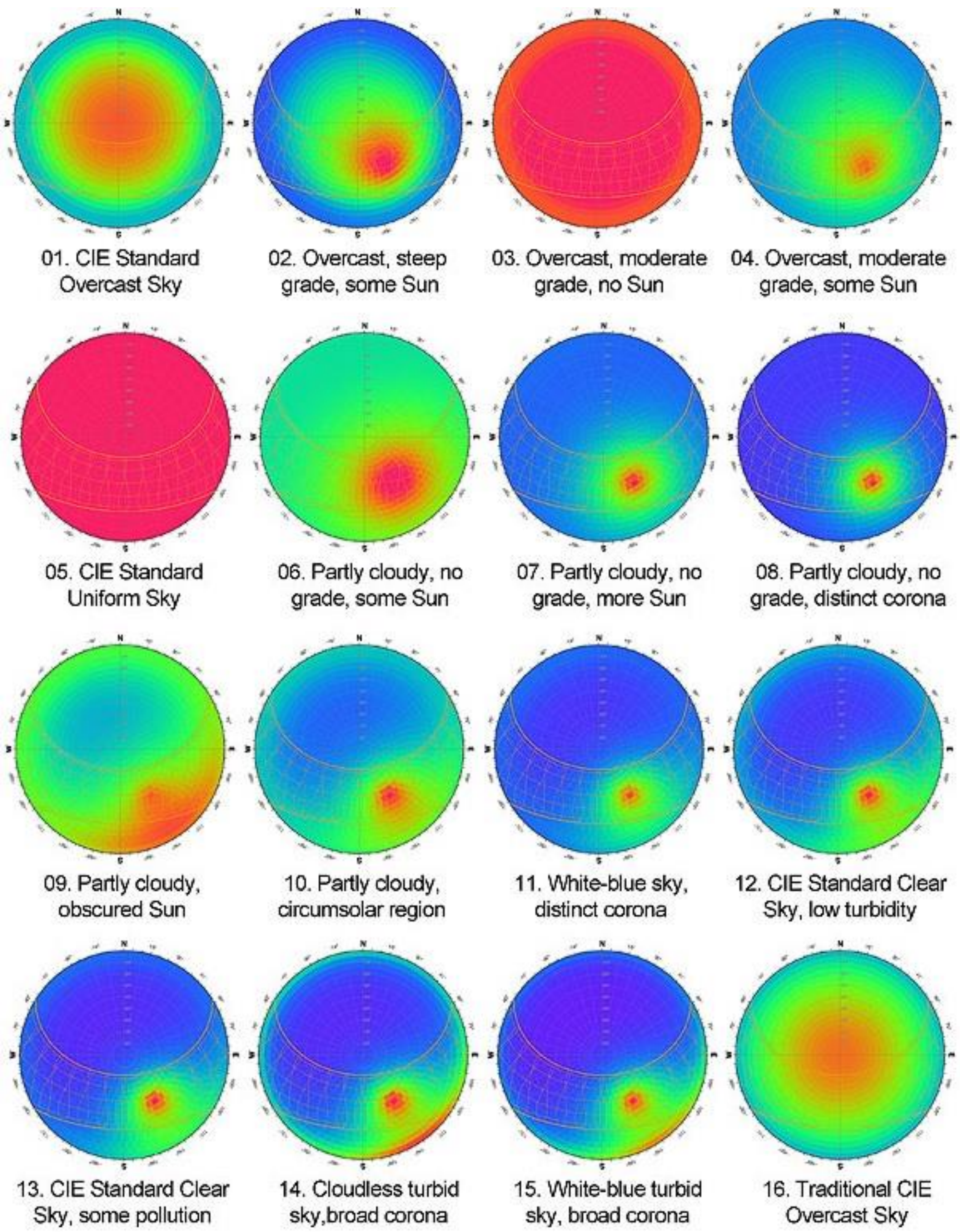

Figure 9. Skies models according to CIE [34, 36]

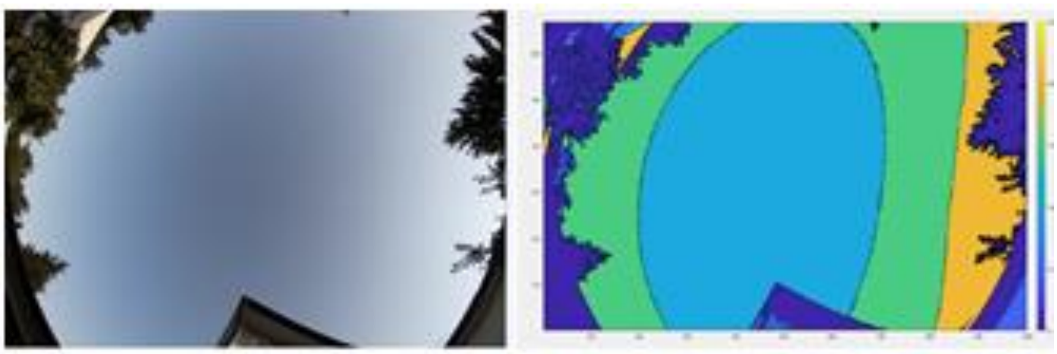

Figure 10. The distribution of sky luminance during the day is made with a matrix luminance meter

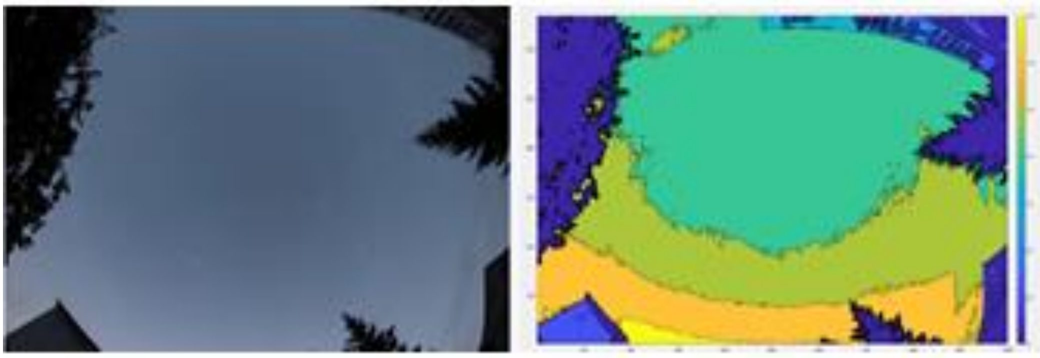

Figure 11. The distribution of sky luminance during the night is made with a matrix luminance meter

The Skywatcher system with a mounted conventional luminancemeter sufficiently carries out the measurement according to the Tregenza model. The luminance values of the sky in the north-south, west-east directions (fig. 9 and 10) coincide with those given by CIE as normative for the transparent sky case (model 1). The measured luminance values for the night sky in the studied area are from 380 to 500 cd/m² in the north-south direction and from 350 to 550 cd/m² in the west-east direction, was shown on figures from 12 to 15. Luminance distribution charts were made with angular resolution of 6 degrees (along N-S direction) and 9.6 degrees (along W-E direction) In turn, for the daytime sky these values range from 3200 to 7000 cd/m² (north-south) and from 3400 to 4500 cd/m² (west-east). The daytime luminance value is approximately 10 times higher than the luminance of the night sky [31]. The luminance values measured with the SkyWatcher system indicate a different than expected luminance distribution. It is closer to model No. 12, where the maximum luminance is related to the position of the sun. It turns out that it is impossible to determine the type of sky by looking at the image recorded with the camera.

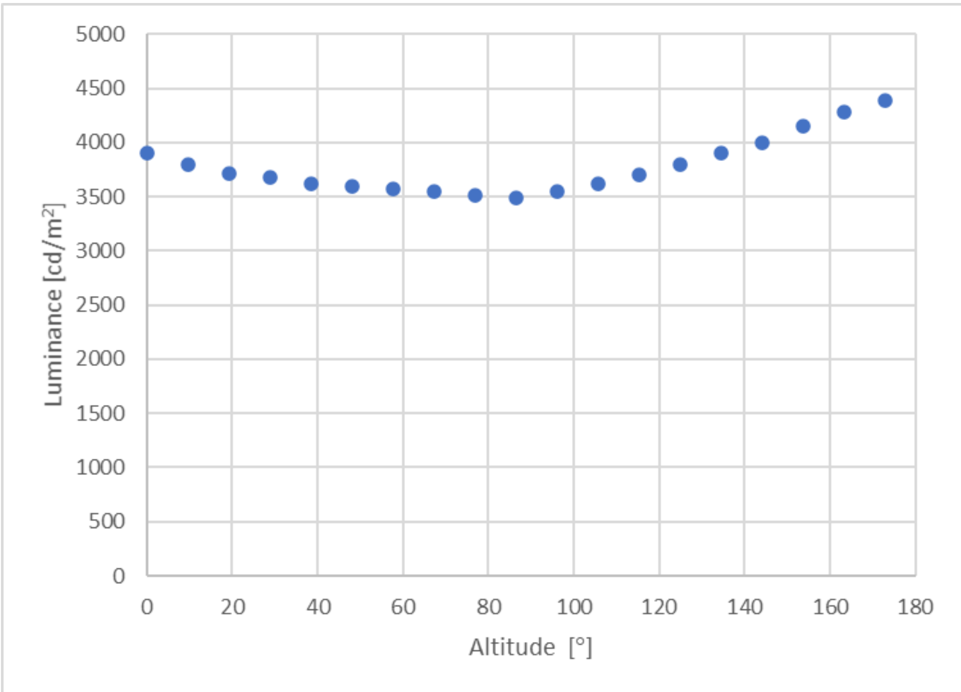

Figure 12. Luminance distribution towards W-E made using the SkyWatcher system with a luminancemeter of sky luminance during the day

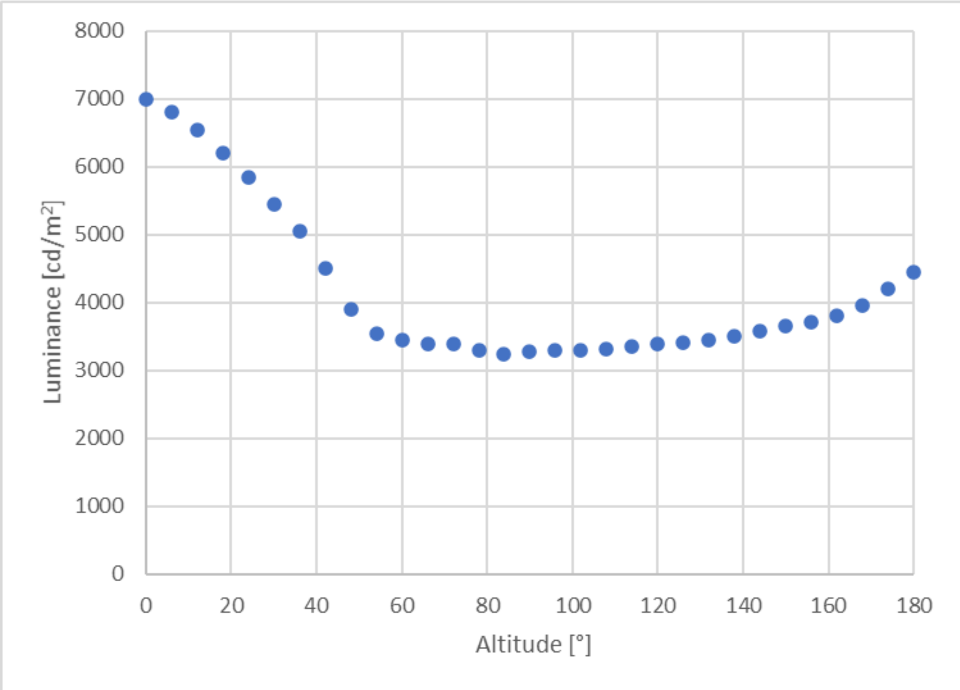

Figure 13. Luminance distribution towards N-S made using the SkyWatcher system with a luminancemeter of sky luminance during the day

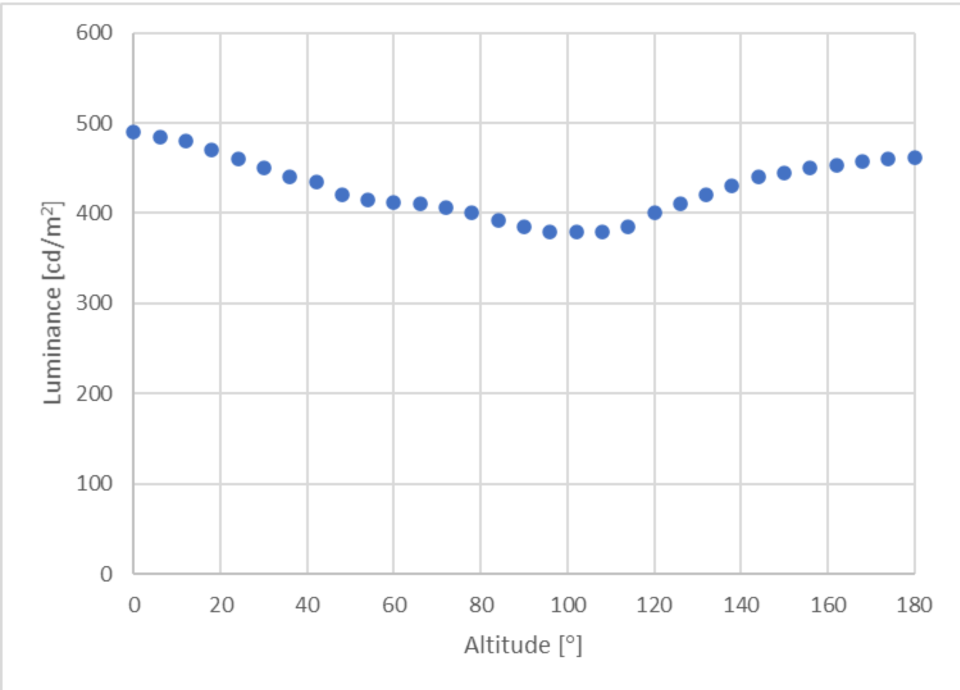

Figure 14. Luminance distribution towards W-E made using the SkyWatcher system with a point meter of sky luminance during the night

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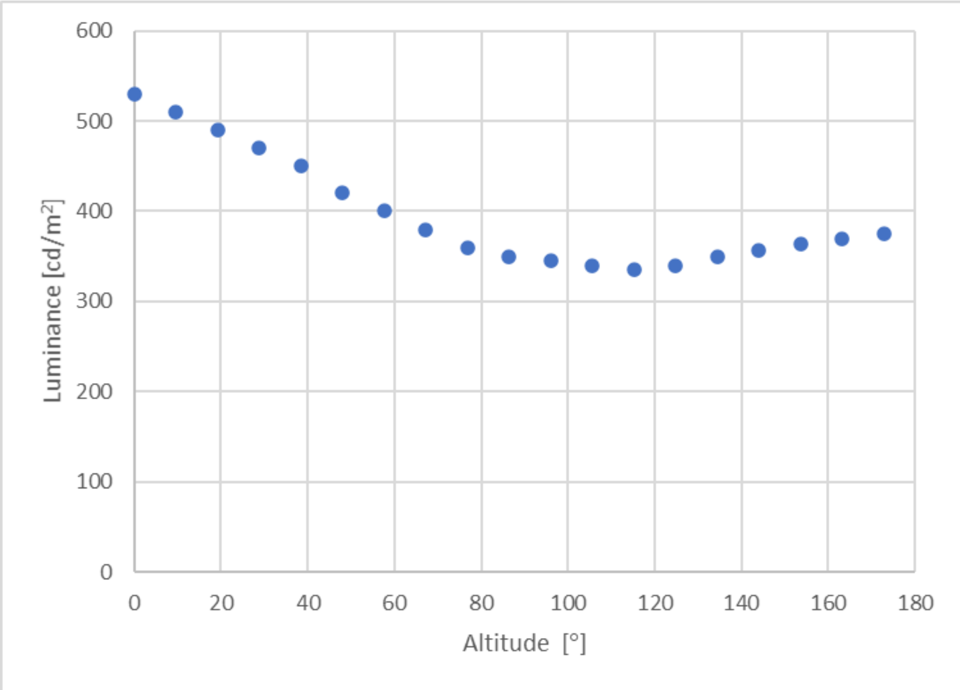

Figure 15. Luminance distribution towards N-S made using the SkyWatcher system with a point meter of sky luminance during the night

5. Conclusions

This article presents the concept of sky luminance distribution analysis by direct measurement using the SkyWatcher Virtuso measuring system with a typical point luminancemeter. The time needed to measure the entire sky, assuming a continuous measurement mode, does not exceed 4 minutes. This is half the time measured using a matrix luminance meter, but it is not burdened with geometric errors introduced by the optical system and errors associated with spectral correction.

SkyWatcher Virtuoso allows you to accurately and repeatably aim the luminance meter at designated measurement fields, in accordance with designated path of meas-urement point. This system has high precision angular positioning and its accuracy does not exceed 12 '' (0.033 °). Therefore, it is possible to use the SkyWatcher to measure lumi-nance distribution, evaluate UGR glare index and luminance distribution on the road. Measuring the luminance distribution on a surface requires a series of measurements. It is possible to use a matrix luminance meter, unfortunately this device is very expensive, but it allows to obtain a high-resolution luminance distribution map in the form of an image [15], consistent with resolution of CCD / CMOS matrix in device. The SkyWatcher Virtuoso control system allows the use of a conventional luminance meter. In this case, the resolu-tion of luminance distribution depends on density of measuring points defined in Sky-Watcher, and results can be summarized in the luminance values table.

In addition, instead of the luminance meter, it is possible to install actinometric apparatus and measure for example direct radiation using a pyrheliometer or by using the diaphragm attached to the Skywatcher measurement of scattered radiation in "on-line" mode.

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

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