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*Article*

# Study on the Change Characters of the Urban Spatial Light Pollution from Ground to Zenith

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**Abstract:** As the problem of light pollution becomes more serious, more and more scholars pay attention to this issue and carry out related research. In the perspective of cities, the measurements of light pollution mainly focus on the brightness of the sky or artificial lighting on the ground. However, there is lack of research on the whole urban space. With the two-dimensional brightness analyses, this paper processes the changes of the light environment of the whole urban space into image quantization. It gets the 3D and 2D light environment changes of luminance distribution, color temperature distribution and chromaticity in the three space layers, the ground layer, the urban canopy layer and the sky layer, from dusk with natural light to night with artificial lighting completely. It is found that the brightness difference between the light environments among the three city levels gradually reduces with the measuring time, and the final values maintain at 0.11~0.25cd/m$^2$. In the ground layer, the light environment is mainly affected by the lighting facilities, and vegetation can prevent the light from scattering up. The light environment of the urban canopy layer is the brightest in the whole city space and has the largest influence on the sky layer. The color concentrates in the range of yellow and red. The color temperature near the ground distributes in 3000K~15000K, and near the sky distributes in 2300K~2700K which is warmer than the natural night sky. The sky brightness of Dalian city is about 951 times than the natural night sky.

**Keywords:** light environment; artificial light; natural light; function distribution; optical parameter

## 1. INTRODUCTION

Light pollution problems have become increasingly prominent with the development of city modernization [1-2]. A large number of studies have found that light pollution not only seriously affect the astronomical observation [3-6], but also the ecology [7-9] and human health [7, 10-11]. The light pollution has become one of the city problems to be solved urgently [13]. Meanwhile, the scientific ways to detect and evaluation the light pollution are the necessary condition for the study of the urban light pollution and the effective measures to protect the night sky [14].

In the existing research results, several of the ways to observe the light pollution have been devised. According to the characteristics of observation and analysis, the current methods are mainly divided into two kinds, the directly measurement from the ground and the ground measurement combined with satellite images [1]. Duriscoe et al (2007) applied a mosaic of CCD images to assess and observe the brightness of the entire night sky over the American National Park

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[15]. And the measurements were calibrated using images of standard stars contained within the raw data. Rabaza (2010) used the CCD camera to take pictures of the urban night sky, analyzed them by VBG and assessed light pollution distribution of the sky [16]. Biggs et al. (2012) treated the urban business districts of Perth, Western Australia as the test center and created a quasi-random sampling with a grid of size approximately 2.5 × 2.5 km from the urban to the suburb across Perth [17]. They measured the night sky brightness with SQMs and GPS navigation system and manage data obtained to draw the contours of night sky brightness. Kuechly (2012) described and mapped the high resolution (1 m) mosaic image of the city of Berlin, Germany at night. They analyzed and identified the major sources of the city light pollution, compared the light emission from differently sized land use classes and found the dominant source of zenith directed light pollution from lighting associated with streets [18]. Pun et al (2014) continuously observed the night sky of 18 districts in Hong Kong over a long period of time with the Sky Quality Meter (SQM) photometers and established the night sky brightness model based on the district assortments. The model exhibits the night sky luminance distribution and provides the data to help the outdoor lighting designs in Hong Kong [19]. Xiaoming Su established the brightness-gray model of Hohhot, Inner Mongolia through combining the actual measurement on the ground with the grey-scale map of satellite image of the night sky brightness over the city [20]. In addition, Pierre brunet et al captured the 360-degrees images of the sky in the city at night with the CCD camera equipped with the fisheye lens. This method avoids the problem of color difference caused by jointing images captured at a single time.

According to statistics for the studies on the city light pollution at present, it is found that they are more focused on the light pollution in the single level like the night sky. However, the number of studies on the changes of light environment in the vertical direction of the whole urban space is relatively less. In order to study the light environment change characters of the whole city space, this paper firstly captured images of the measurement area at the top of the city's high-rise building. Then it respectively processed the images into a set of diagrams, including diagrams of the brightness distribution, color distribution and color temperature distribution, and analyzed their changing characteristics with time. Moreover, it analyzed light environment changes of each city level from the transverse direction and the mutual relationship between these three levers from the vertical direction. Finally, this paper shows the change characteristics of light pollution in urban space and the light pollution condition of the measurement area.

## 2. THE CAUSE OF SKY GLOW AT NIGHT

Since the 20th century 60s, astronomers have researched the city’s light pollution through observing the night sky. In 1995, the International Dark Sky As association divided the night sky into 7 magnitudes based on the visibility of the stars in the sky [21–23]. According to this rank, the dimmest stars only can be observed by the naked eyes in the 7th magnitude sky. In the other words, the 7th magnitude sky is the most primitive dark sky. In 2001 Sky and Telescope, John Porter divided the night sky into magnitude 1 to 9 by visual inspection to measure the sky glow [24–26], and thus to reflect the influence of light pollution on the sky. Generally speaking, the classification of the night sky provides a simplest and most direct method to evaluate the degree of light pollution in the night. According to the observation of the galaxy, stars, sky color and other targets, it can be very intuitively to evaluate the effects of light pollution levels on urban night sky. This method can only reflect the influence of light pollution in the sky. However, the light pollution actually exists in the entire city space. The night light environment is mainly made up of two parts: artificial lightning and natural lighting [27–28]. But the former has more influence than the latter on the night environment at present because of the development of lighting facilities [29]. In the entire city space, the light produced by artificial lighting affects the region outside the outdoor lighting area, due to direct radiation and indirect reflection. Furthermore, the parts of these light that are diffused into sky will be scattered into city again by air molecules and aerosol. Thus it cause light pollution such as sky glow, as shown in Figure 1. Moreover, the longer the path length of light cross through the aerosol, the more lights will be scattered.

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With the deepening of the study on the city night light pollution, it is found that light propagation in space is affected by the above-mentioned elements and also air particles, cloud, vegetation and so on. According to the difference value of diameter size between photon and molecule in the air, light scattering also is divided into Rayleigh scattering and Mie scattering. When the diameter size of the molecule, is smaller than the wavelength of light, the light propagation is Rayleigh scattering which is equal forward and backward scatter and caused mainly by air molecules. When the diameter of the molecule is similar to or larger than the wavelength of light, it is Mie scattering which is no wavelength dependence and very directional and caused by aerosols, water droplets and dust. In 2001, Henrik W J presented a physically-based model of the relationship between the night sky and the illumination coming from the Moon, the stars, the zodiacal light, and the atmosphere, using physically-based astronomical data, both for position and radiometry [30]. In 2006, Baddiley C reported and analyzed the relationship between urban sky glow and the atmospheric scattering in the sixth European Dark Sky Seminar [31]. He found that sky glow is a phenomenon caused by upward artificial light and the light reflected by the air molecules and aerosol to the sky. The atmospheric aerosol scattering (Mie scattering) take a leading role in the lower atmospheric layer, while atmospheric molecular scattering (Rayleigh scattering) gradually replaces it with increasing altitude. It is shown in Figure 2. Therefore, the condition of the night the light environment and light pollution are different in the different levels of urban space. Based on the characteristics of the light pollution, this paper is focused on the observation on the light environment changes of the whole city space.

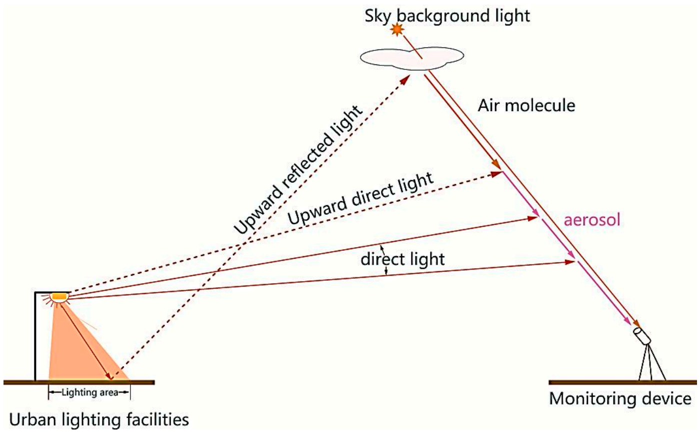


**Figure 1.** The propagation of urban artificial lighting in urban space

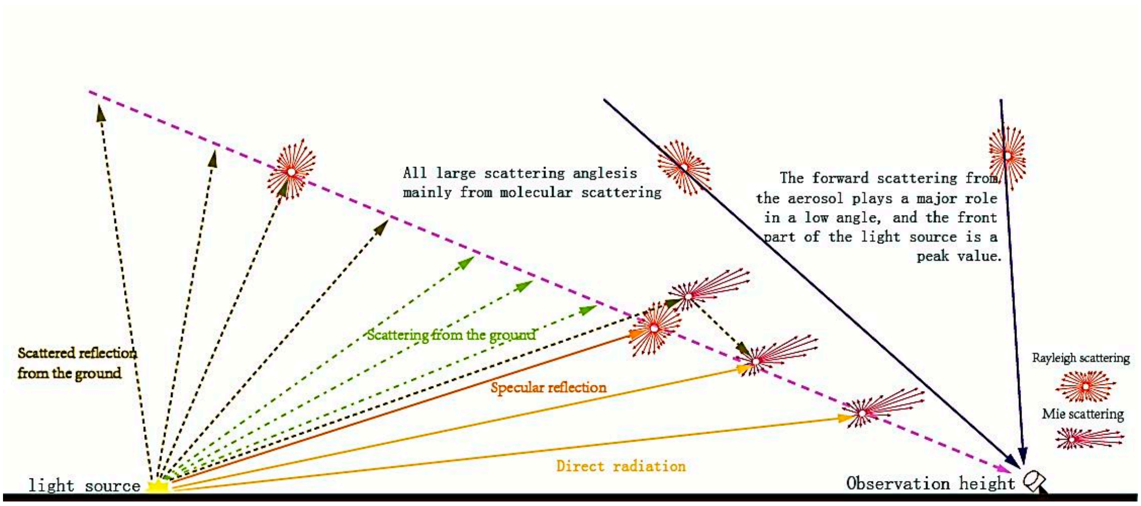


**Figure 2.** The relation between the light propagation and the observation point in the urban space

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## 3. METHOD

### *3.1. the Measurment Object*

This paper selected the Dalian University of Technology and its surrounding region as the objects of observation for studying the night brightness changes. This region is located in the southwest of Dalian. The main illuminations of this area are road lighting, square lighting, commercial lighting from the vicinity as well as architectural lighting from teaching building and dormitory area.. The measuring time is from 7 pm to 9 pm, July 2015, covering the changes of light environment from natural lighting to artificial lighting. The weather during the observation time was cloudy with a slight fog over the city. The temperature was 22 degrees and the wind speed was 4-5 metres per second. Three main indices have been established in this paper, luminance, color temperature and chromaticity. According to the main type of light sources, the whole observation period was divided into four stages. The four stages and time nodes of each are: the stage of natural lighting (pm 7:20), the stage of natural lighting-artificial lighting transition (pm 7:40), the stage of artificial lighting (pm 8:00) and the stage of artificial lighting stabilization (pm 8:20).

### *3.2 RESEARCH METHOD*

This paper divided the urban light environment into the ground layer, the canopy layer and the sky layer from the ground to the sky, according to the distributions and characteristics of city night light sources and observation angles. In the urban ground layer, light environment is closely related with artificial lighting, such as architectural lighting, street lighting, plaza lighting and commercial lighting, associated closely with human health and environment of life (Figure 5). The urban canopy layer, referred as the urban hollow layer also, is located in the average elevation of the rooftop of buildings. The natural lighting from the sky layer and the artificial light from the ground layer make up into the light environment of this layer. Besides, it is influenced by the urban lighting planning. The urban sky layer also called as the zenith is influenced by natural conditions and the artificial lighting environment.

This paper selected the highest point in the northern of the Dalian University of Technology as the place of observation. It is the commanding height of the region and is located in the canopy layer. Therefore, it can observe and measure the complete urban light environment containing the ground, the canopy and the sky. The distribution of the main light sources and the function distribution around the observation area are shown in the Figure 3 and 4.

This observation experiment was recorded by taking a group of photographs every 20 minute with the Two-dimensional Color Brightness Meter CA-2000 with a wide-angle lens CCD. Then the real images of the area were captured for the four time nodes from the stage of natural lighting to the stage of artificial lighting stabilization. The images and data about luminance, chromaticity and so on are quantitatively processed and analyzed with image processing software CA-S20W, so as to obtain the distribution of the brightness, the chromaticity and the color temperature of the overall space with the lighting environment. Finally, the paper studied the distribution characteristics and mutual influence relationship of the light environment from the perspective of urban space and obtained the basic distribution characteristics of light pollution in the overall space.

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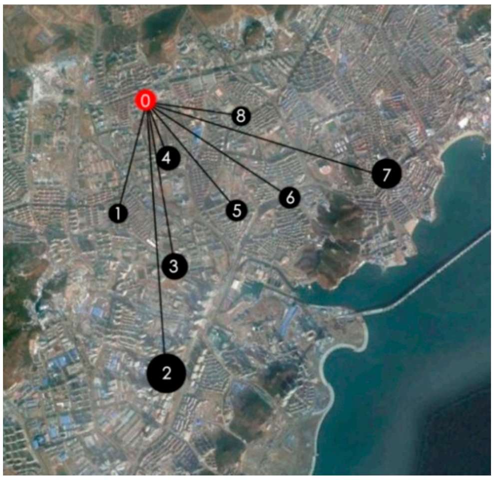


**Figure 3.** The distribution of the main light sources around the observation area: point 0-observation point in the Dalian University of Technology; area 1-Wenhui Community; area 2- the business district in Qixian Ling; area 3- Dalian Maritime University; area 4- Dalian University of Technology; area 5- Dalian Light Industry School; area 6 - Xueyuan square; area 7-Heishijiao business district; area 8-Residential areas like Digital Home

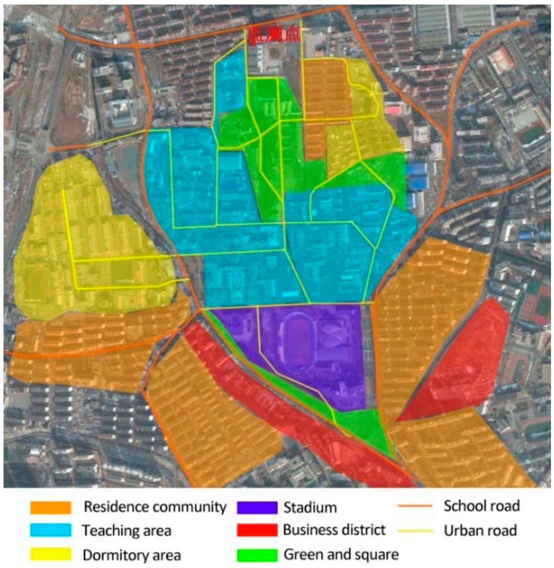


**Figure 4.** The function distribution of the Dalian University of Technology and surrounding areas

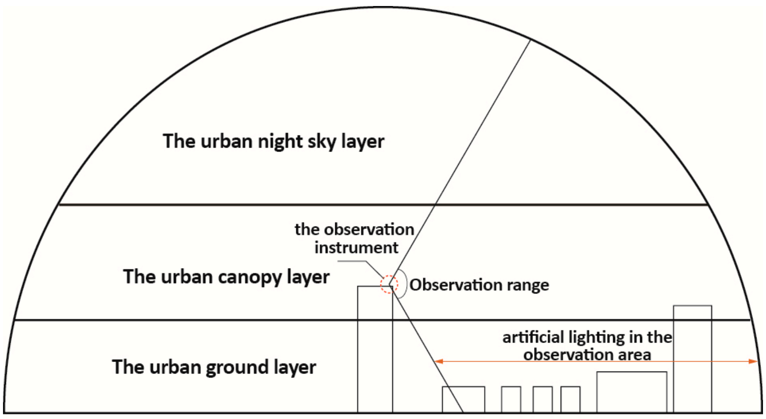


**Figure 5.** Schematic diagram of the three urban space layers and the observation points

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# 4 CONSEQUENCE AND ANALYSIS

## *4.1 THE LUMINANCE CHANGE FROM GROUND TO ZENITH*

This paper took photographs of the observation area in multiple exposures by the Two-dimensional Color Brightness Meter equipped with wide-angle lens CCD and captured the real images as shown in Figure 6. They exhibit respectively the actual condition of the light environment for the four stages of the changes form the stage of natural lighting to the stage of artificial lighting stabilization. It can be seen from the real-life images that the weather conditions and lighting conditions change in the overall space of the observation area. The ground layer of the observation covers schools, residential areas, plazas and green areas. It can be seen from Fig. 6(b) and (c) that the light environment of the urban night sky layer is still affected by natural light before entering the stage of the complete artificial lighting. When the environment of artificial lighting is stable, the artificial lighting has an even worse effect on the night sky layer. At this stage, the light pollution is the most serious. In addition, the light environment of the urban ground layer is related to the distribution of urban functions. Architectural lighting and road lighting have the most obvious impact on the surface light environment, while the regional light environment in the green area has the lowest brightness due to less upward projection.

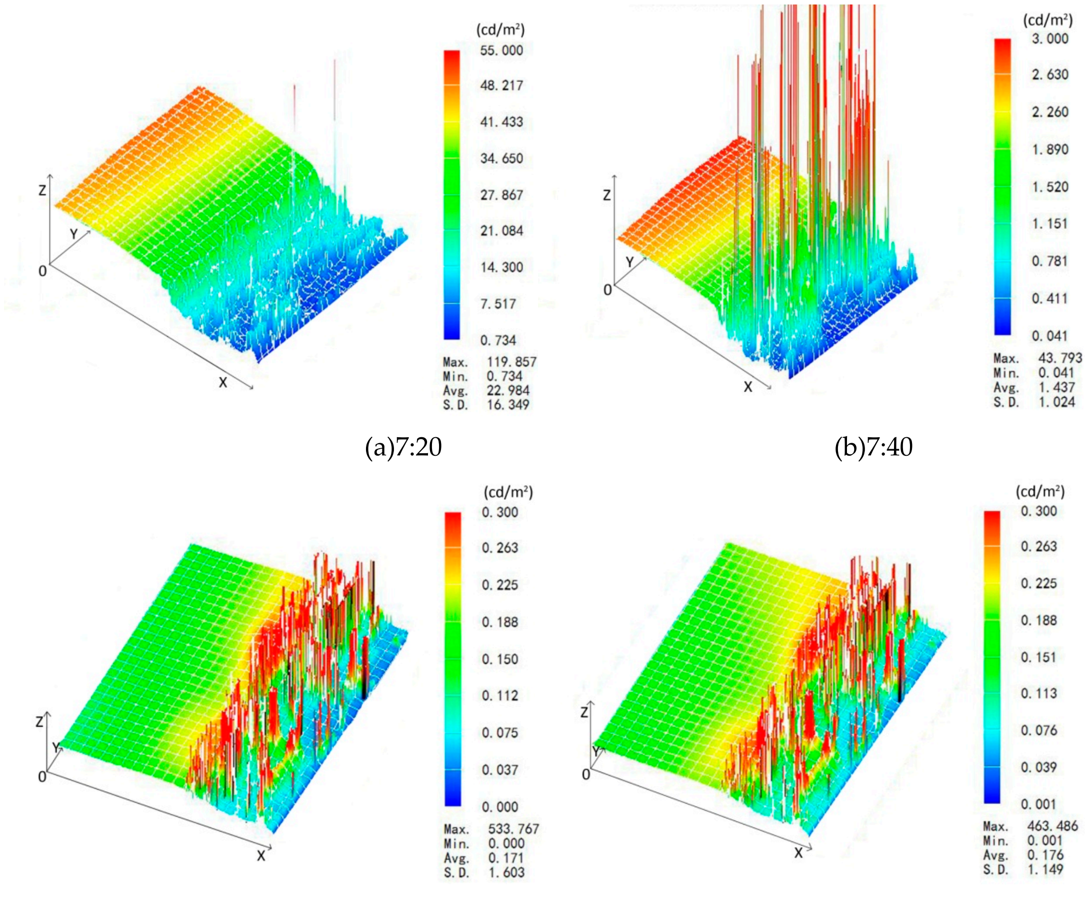
(a)7:20 (b)7:40

(c)8:00 (d)8:20

**Figure 6.** The real images of the observation area focused on the varies of the light environment with time at four key times. The figure a shows the condition in the natural lighting environment at 7:20 pm, the figure b shows the mixed condition in the environment changing from natural to artificial light at 7:40, the figure c shows the condition in the initial artificial lighting environment at 8:00 and the figure d shows in the complete artificial lighting environment at 8:20.

These actual images of the entire light environment are processed into visualization of the luminance with the image processing software, as shown in the Figure 7. In the three-dimensional luminance distribution maps, the X axis shows the space in the vertical direction which includes the night sky layer, the urban canopy layer and the ground layer in sequence from zero to the lager value. The Y axis indicates the horizontal direction and its values from the zero to the lager value are consistent with the actual images from left to right.

Through analyzing the luminance distribution maps, it is found that the urban overall spatial light environment is obviously changing regularly. In the period from the natural lighting environment at 7:20 pm to the mixed lighting environment with natural and artificial light at 7:40, the light environment of the urban night sky layer and the canopy layer are mainly affected by the natural lighting and the night sky layer is brighter than the canopy. With the gradual disappearance of natural light and the increase of artificial light, the brightness of the urban night sky layer and the canopy layer gradually increase. In addition, the brightness in the urban ground layer changes with artificial lighting condition in different areas. In the artificial lighting environment of the canopy layer is mainly affected by the lighting from the ground layer, and its brightness is obviously higher than that of the night sky layer. In the urban ground layer, the light environment of the green area is the darkest because of the less lighting facilities in the green region and the masking effect of the plant on lighting. The light environment of building areas is the brightest and the brightness positively correlated with the building size, building height, the external decorative lighting and the open condition of indoor lighting. As the sizes of the buildings grow larger and the heights become higher, the brightness of the overall urban space environment is higher and the light pollution becomes worse. The brightness of the regions with the street lighting and plaza lighting is between the green areas and the building areas, which is due to the masking effect of the plants.



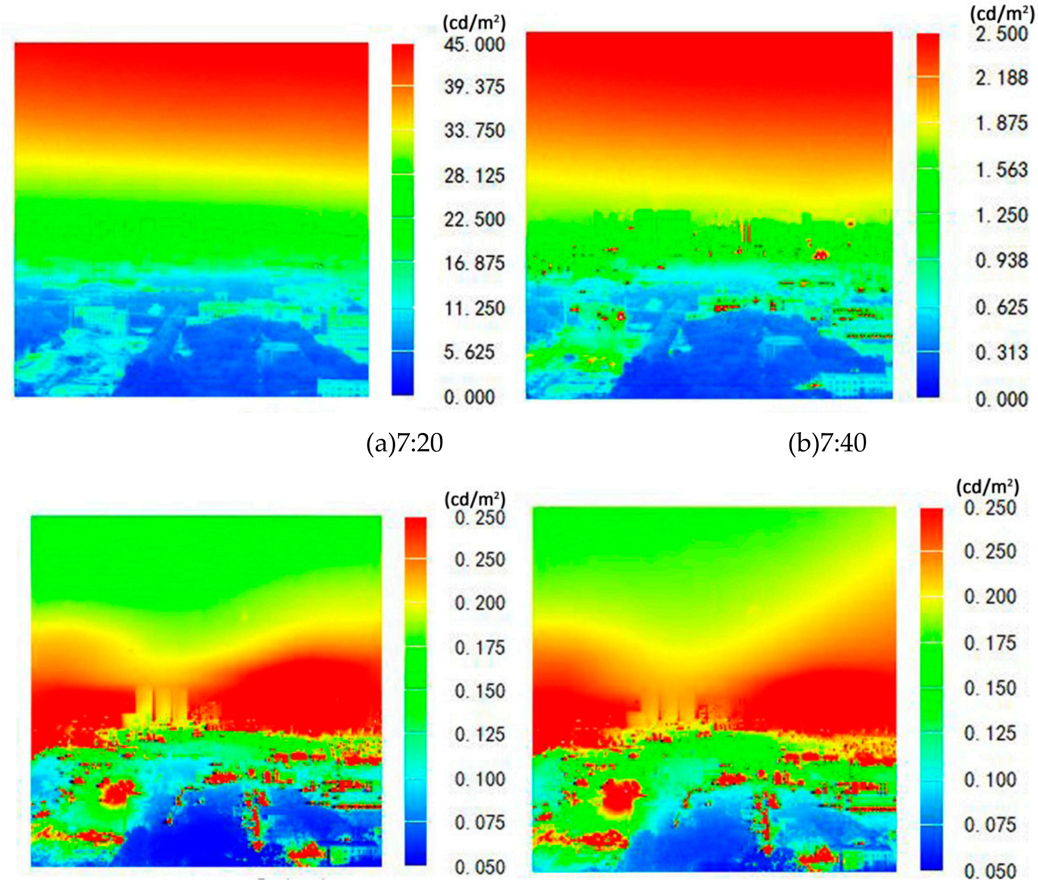

(a)7:20 (b)7:40

(c)8:00 (d)8:20

**Figure 7.** The three dimensional luminance distribution of the light environment

*4.2 THE LUMINANCE CHANGES IN EACH URBAN LAYER*

By analyzing the three-dimensional distribution, it is found that the light environment of each spatial level of the city has its own characteristics. Therefore, these actual images are processed into the two dimension brightness visualization in the vertical direction, as shown in Figure 8. By analyzing the brightness distribution maps corresponded with the actual spatial layer, it is obvious that the brightness of the vertical light environment has an obvious hierarchical distribution closed to the three urban layers divided in this paper. At the same time, it can be seen that there is a significant mutual influence relationship between the spatial layers. For the further study, this paper subdivided the spatial layers in the vertical direction into the five horizontal layers that are respectively the urban ground layer, the canopy layer near the ground, the urban canopy layer, the canopy layer near the sky and the urban night sky layer, as shown in Figure 9. Then this paper made a comparison between the brightness distributions of the five horizontal layers at each observation time by image processing software. As shown in Figure 10, it gets the linear comparison charts of the brightness in the five horizontal sections.




(a)7:20 (b)7:40

(c)8:00 (d)8:20

**Figure 8.** The two dimensional brightness distributions of the observation area in the vertical direction

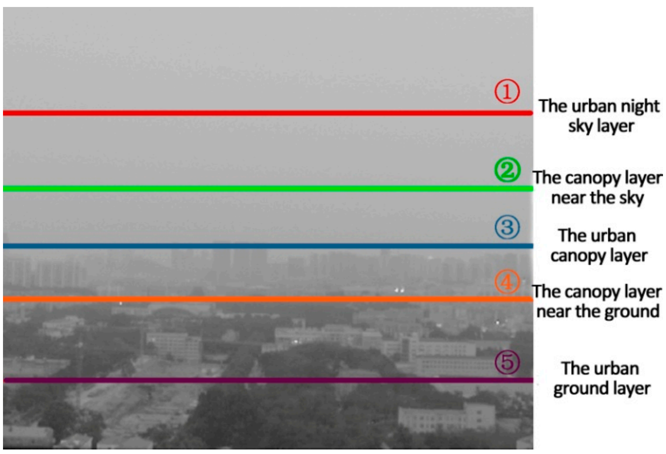



**Figure 9.** The further layers subdivided in the urban vertical direction

Through comparing the brightness of these five horizontal sections at each observation time, the following conclusions can be obtained.

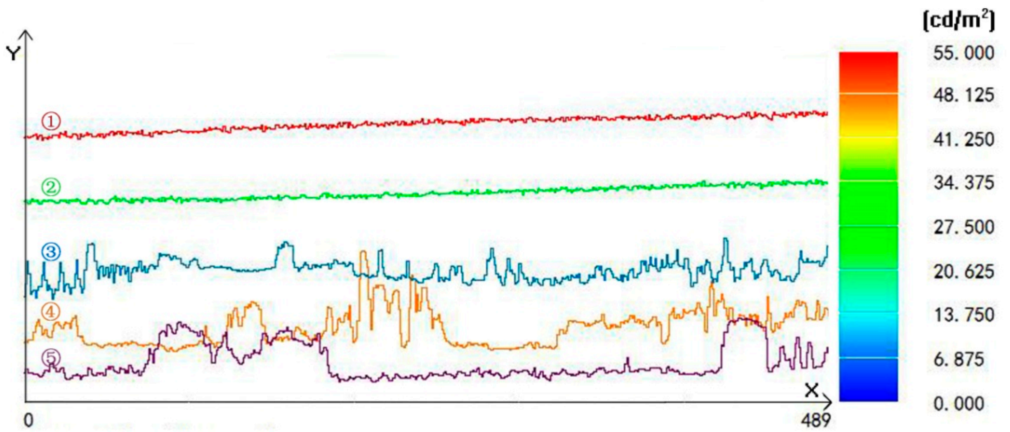
1) During the entire monitoring period, it is found that the differences of luminance values between each horizontal section gradually decrease with times except the obvious artificial lighting areas. Eventually the luminance values of the region remain around 0.11~0.25cd/m².

2) In the period of artificial lighting dominating, the urban canopy layer and as well as its adjacent area have the highest luminance value and the most severe the light pollution. This is because that these three layers have large numbers of the air molecules and aerosol particles and intense Rayleigh scattering and Mie scattering. Therefore, this layer is the brightest in the urban space.

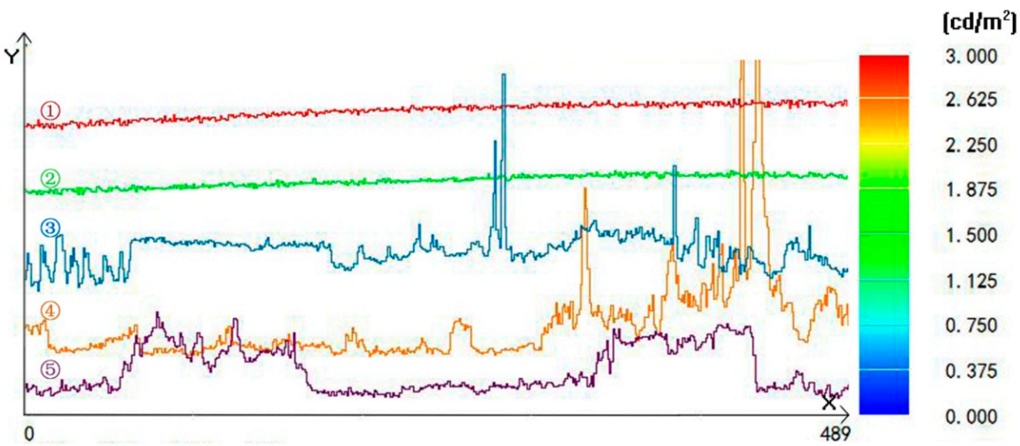
3) With the degradation of the brightness of the natural background, the brightness of the light environment in the urban night sky layer is gradually decreased and is susceptible to commercial lighting in the distance. In the period of stable artificial lighting, the average value of the luminance of the sky layer is 0.20cd/m², closely 951 times higher than natural dark night sky ( = 2.1 x 10-4cd/m²).

4) In the urban ground layer, the vegetation has obvious masking effect on light diffusion caused by artificial lighting. Therefore, the light environment of some parts of the canopy layer, above the vegetated area of the ground layer, is darker than others areas of the same layer. Because the light environment of the urban sky layer is affected by the whole urban lighting, the brightness differences between the canopy layer and other layers are not obvious.

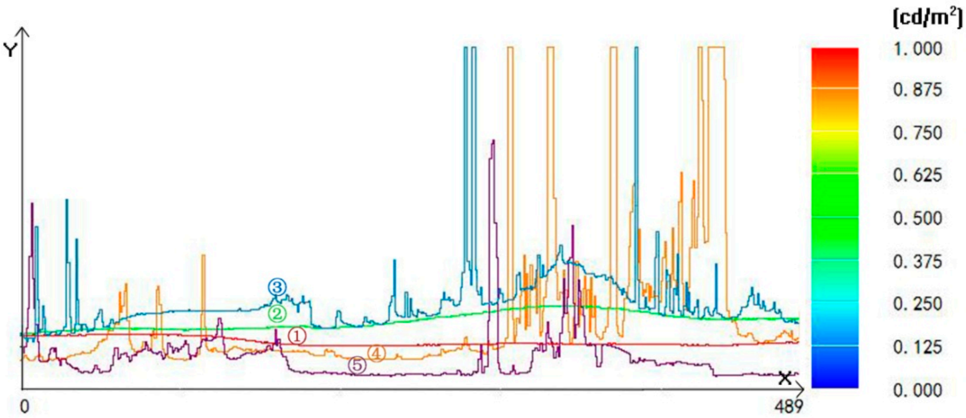
5) The light environment of the canopy layer near the sky is obviously influenced by the urban canopy layer and the canopy layer near the ground and therefore has an impact on t the light environment of the urban night sky layer.  Since the large amounts of scattering light in the canopy layer, the difference of the brightness of the night sky layer over the whole city is not obvious in the same period.



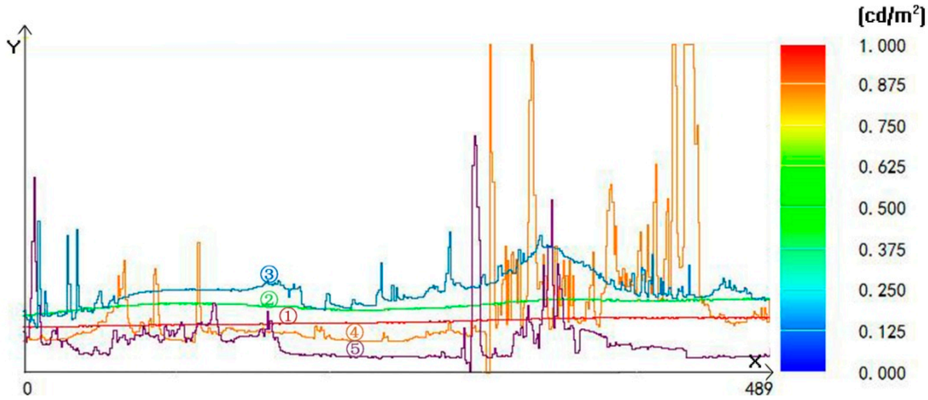

(a)7:20



(b) 7:40




(c)8:00




(d)8:20

**Figure 10.** The luminance changes of the five urban space layers at four key times. As the display range of luminance in (c) and (d) is between 0 cd/m² and 1 cd/m², so the parts more than 1cd/m² is displayed as a horizontal line.

As the study found, the light environment at the overall urban layers is mutually influential. In order to study the influence between these five spatial layers, this paper selected a vertical cross section of in the observation window, as shown in fig. 11, and compared the luminance distribution variation in the vertical direction represented in the line graph, as shown in figure 12. In the Figure 11, the ground layer contains green areas, construction areas and road lighting. In the line graph, the X-axis indicates the space from the ground to sky, and the Y-axis indicates the luminance value.

By analyzing the image, it is found that as the amount of artificial light increases and the brightness of the natural light decreases, the brightness of the night sky descend and keep stable at the end. . The light environment of the urban canopy layer is brighter than the night sky layer and the area near the ground is easily influenced by building lightings. In addition, the change of the light environment in the ground layer is closely related to the urban internal facilities, such as architectural lighting and road lighting.

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**Figure 11.** The vertical cross section of the observation region selected in the vertical direction is showed by the black line in the image

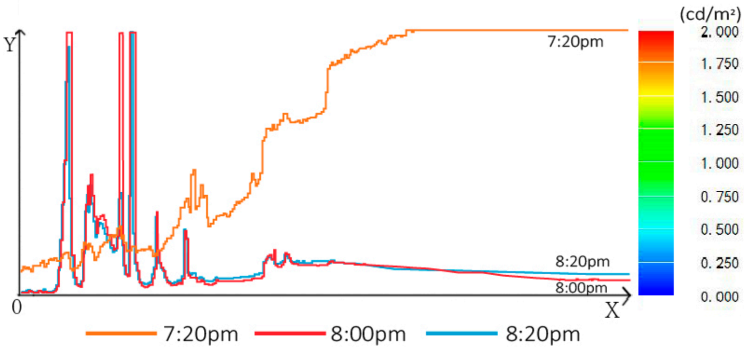
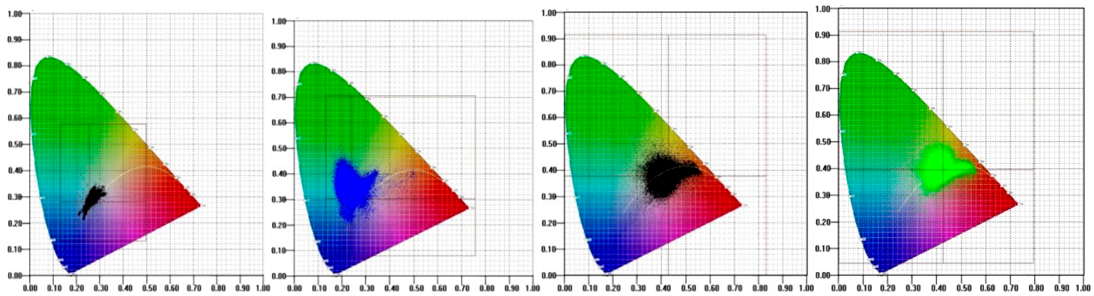



**Figure 12.** The luminance comparison of the vertical cross section at three key times, and as the display range of the luminance is between 0 cd/m$^2$ and 2 cd/m$^2$, so the parts more than 2 cd/m$^2$ is displayed as a horizontal line

*4.3 THE CHANGES OF THE CHROMATICITY DISTRIBUTION OF THE URBAN SPACE WITH TIME*

This paper drew the chromaticity of each point in the actual images into the chromaticity diagram and got the chromaticity distribution maps of the observation region in each period with the image processing software, as shown in Figure 13. By comparing the images, it is found that the overall light environment chromaticity value moves regularly with the change of illumination. At dusk, when the sun has not disappeared, the light environment of the sky is mainly affected by natural light, and the chromaticity of the region distributes intensively around the coordinate point (X=0.28, Y=0.28) in the chromaticity diagram which belongs to the color region of blue and white conformed to the natural condition. With the disappearance of the sunshine and the gradual opening of the artificial lighting in the transitional stage from natural lighting to artificial lighting (as shown in figure 13(b)), the chromaticity distributes intensively around the coordinate point (X=0.24, Y= 0.32) and the chromaticity distribution of the light environment is homogeneous. In the stage of completely artificial lighting, as shown in figure 13(c) and (d), chromaticity points, the color are red and yellow, are concentrated in the coordinate point (X=0.44, Y=0.4) . That is because that the colors of the outdoor lighting are mainly red and yellow and the red light in air have a longer propagation path and less loss. In addition, it is found from the changes of the chromaticity over the period of the study that the light environment is interfered by light pollution from the commercial lighting and architectural lighting nearby the canopy layer.

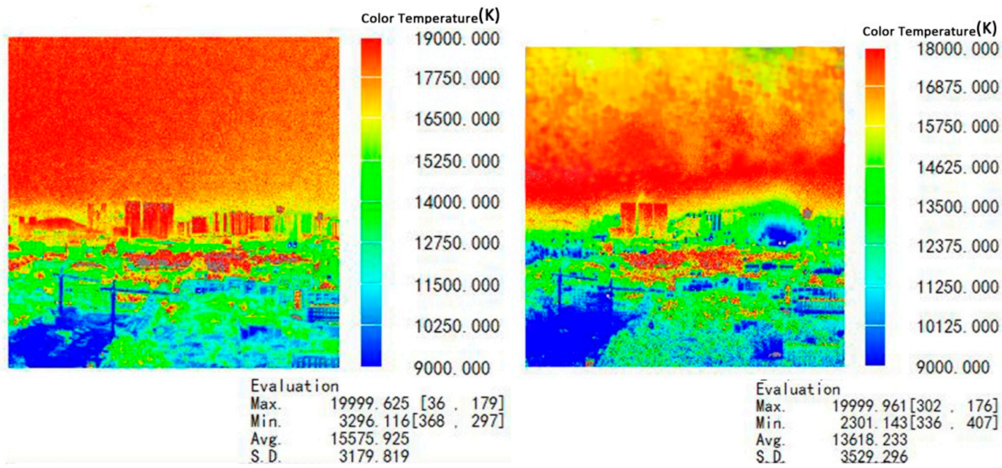


(a)7:20 (b)7:40 (c)8:00 (d)8:20

**Figure 13.** The diagram of the chromaticity distributions of the observation region from the pure natural lighting environment to the complete artificial lighting environment

*4.4 THE CHANGES OF THE COLOR TEMPERATURE IN THE WHOLE OBSERVED SPACE*

The paper processed the color temperature distribution of the overall light environment into visual color graphs, as shown in figure 14, with the software. The following findings are based on these color diagrams: 1) In the stage of natural lighting and the transition from natural lighting to artificial lighting, the color temperatures of the observed region distribute mainly between 9000K and 20000K. The urban sky layer has the highest color temperature. Besides, the average value of color temperatures is decreased gradually with the time. 2) In the light environment of artificial lighting, the distribution of the color temperatures is concentrated between 2700K and 3200K. In detail, the color temperatures of the ground layer are distributed between 3000K and 15000K, the color temperatures of the canopy layer and sky layer are between 2300K and 2700K and the actual color temperature of the night sky is warmer than the natural night sky which is 2725K. 3) Distributions of air particulate matters and clouds have an impact on the color temperature of the sky. From figure14 (c) and (d), it is shown that the color temperature values of the sky in the cloud area are near the values of the ground when clouds appear in the sky. Therefore, it is found that air particulate matters and clouds over the city will enhance the influence urban artificial lighting on the night sky. But the specific impact conditions need a further study.

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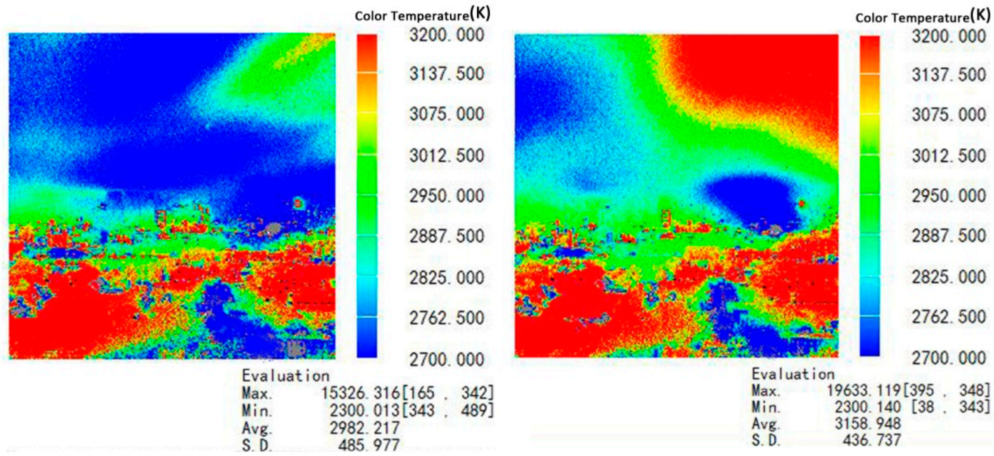


(c)8:00 (d)8:20

**Figure 14.** The images of the color temperature distribution in the whole observation region from the pure natural lighting environment to the complete artificial lighting environment

## 5 CONCLUSIONS

This paper studied the changes of the light environment of each urban spatial layer in the horizontal direction and the relationship of the light environment in the whole urban space in the vertical direction, through observing the whole urban space. These studies can provide help to the studies on the representation and evaluation of light pollution in urban space. In addition, it makes visualization representation of optical parameters of the light environment in urban space, such as luminance, color temperature and chromaticity, by the color images with the two-dimensional color luminance meter and image processing software. These methods provide certain reference values for visualization of light pollution. Through these series of studies, this paper gets the below conclusions. Furthermore, it is needed to further study on the effects of cloud and particle on light propagation and the visualization of light pollution.

1) The luminance difference between the three urban spatial layers gradually reduces with the night time. The brightness values of the whole urban light environment finally maintain between 0.11 cd/m$^2$ and 0.25cd/m$^2$ except those excessive artificial lighting region. The light environment of the urban canopy layer is the brightest of the overall urban space and light pollution in this layer is serious. The average luminance value of the urban night sky layer is 0.20cd/m$^2$ and more 952 times than natural dark night sky (= 2.1×10-4cd/m$^2$).

2) The overall chromaticity distribution region of the city moves gradually from the blue and white region to the red and yellow region with the time from dusk with pure natural light to night with completely artificial lighting. The whole color temperature is decreased sharply and concentrated on the range of 2700K and 3200K in the stage of completely artificial lighting. The color temperature of the sky layer distributes in the higher scope between 3000K~15000K and the color temperature distributes of the ground layer in the lower scope between 2300K~2700K. The actual color temperature of the observed region is warmer than the natural dark night sky.

3) In the urban ground layer, vegetation has an obvious masking effect on direct light and scattering effect from lighting facilities. In the canopy layer, shielding effects are almost non-existent. Therefore, the light environment of this layer is influenced not only by the ground layer but also by the night sky layer.

4) The change of air pollutants and clouds can affect and aggravate light pollution.

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