

Modeling of Natural Lighting Parameters in the Open Air with Intermeradiandiate Luminance Distribution

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Abstract

When simulating outdoor natural lighting, a spherical sky model is used. This is true in a clear sky, but in the presence of clouds, this model does not correspond to reality. This paper presents the substantiation of the sky model in the form of a spherical segment with a standard distribution of the luminance of the semi-clear (intermediate) sky. Moreover, instead of the ratio of illumination, under given cloudiness conditions to illumination with ideal transparency of the atmosphere, which are usually used in European standards, the direct value of cloudiness is used here, taken from the results of long-term observations at meteorological stations. To modeling the parameters of outdoor natural lighting, a more effective and simple mathematical apparatus of point calculus is used, with the help of which a point set of a spherical segment is formed. On the basis of this set, a field of elementary pyramids is created. For each pyramid, using well-known formulas, elementary values of the parameters of natural lighting are determined.

Keywords

Outdoor natural lighting, semi-clear sky, cloudiness, luminance distribution, sky model, spherical segment, point calculus, geometric model.

1. Introduction

In most studies and recommendations on the luminance distribution over the sky and on the determination of external illumination, a hemisphere was taken as a model of the sky [1-5]. This is true for a clear (Fig. 1) sky, but as soon as cloudiness is entered into the sky model, this model is not suitable for a semi-clear (intermediate) sky.



Figure 1: Clear sky

Most cloud types have a flat base at a certain height, which is characteristic of this type of cloud. At this height, the air that has risen from the ground level cools down to the dew point temperature, at which it can no longer cope with the water vapor contained in it. At this temperature, water vapor

GraphiCon 2021: 31st International Conference on Computer Graphics and Vision, September 27-30, 2021, Nizhny Novgorod, Russia

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CEUR Workshop Proceedings (CEUR-WS.org)

condenses and forms droplets of liquid water, which we see as a cloud. For different types of clouds, the height of their location is different [6]. For example, low-level clouds are located at an altitude of up to 2000 m (Fig. 2). Middle-level clouds (Fig. 3), which include cumulus, stratocumulus, cumulonimbus, are located at an altitude of 2000 to 5000 m. High-level clouds – nimbostratus, altostratus and altocumulus clouds – are located at an altitude of 5000 m, etc. For example, in Figures 3 and 4 show stratocumulus and cumulus clouds (all photos are copyright).



Figure 2: Overcast sky



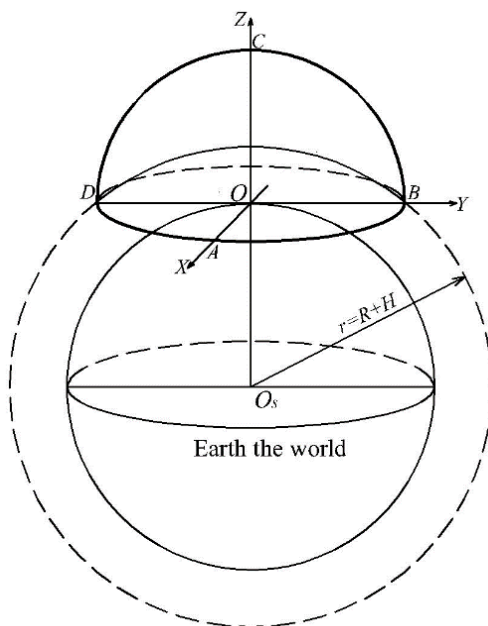
Figure 3: Stratocumulus clouds



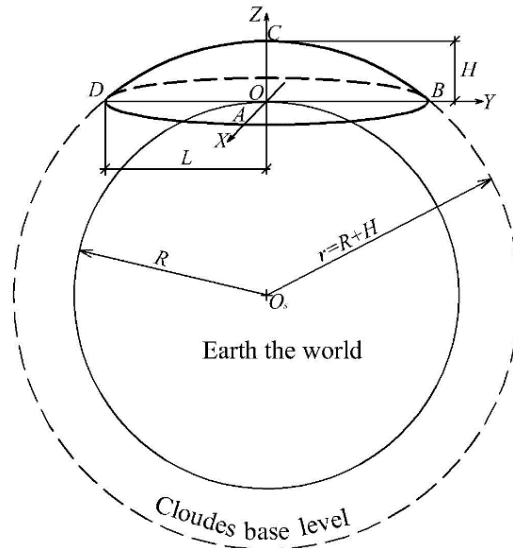
Figure 4: Location of cumulus clouds

The spherical shape of the firmament does not reflect reality in the transition to the assessment of the parameters of natural lighting on the semi-clear sky model (Fig. 5a). This can be seen from the figures 3 and 4 real examples.

The bases of the clouds are located parallel to the earth's surface, so the calculation scheme when determining the light and climatic parameters will look as shown in Fig. 5b.



a)



b)

Figure 5: Geometric comparison of the sky models: a - spherical; b - in the form of a spherical segment

Many researchers have been engaged in models of the distribution of brightness and illumination from different types of the firmament [1-5]. A large number of experimental studies have been carried out on the distribution of brightness over the sky, including intermediate (semi-clear) [4, 5, 7, 8]. Based on the results of these studies, a classification of sky types was carried out [9] according to combinations of regression coefficients that characterize the indicatrix of light scattering in the atmosphere. There are two points to note here. Regression coefficients and their combinations are special cases of physical models. The parameter characterizing cloudiness is not the direct value of cloudiness, but the ratio of scattered radiation to total radiation.

The purpose of this work is to modeling outdoor natural lighting with a semi-clear (intermediate) distribution of the sky luminance, as well as to develop a method for calculating the parameters of the light field using the mathematical apparatus of point calculus. This will make it possible to form a more realistic picture of natural lighting in rooms with light openings of any shape, which are arbitrarily located in space.

To achieve this goal, you must complete the following tasks:

1. Construct a geometric model of the luminance distribution of the semi-clear sky and determine its computational algorithm based on point equations.
2. To improve the methodology for determining the main parameters of outdoor lighting, taking into account the refined geometric model of the semi-clear sky luminance distribution.

2. Geometric model of the semi-clear sky luminance distribution

To solve the set tasks, we present a diagram of a spherical segment with interconnected parameters (Fig. 7) [10]:

$$L = \sqrt{H(2r + H)}, \quad (1)$$

where r is the radius of the full sphere from the center of the Earth to the base of the location of the clouds, km;

L is the distance of the horizon line from the center O (observer), km;

H is the height of the spherical segment from the center O to its zenith C , km.

The ratio of the base height for different types of clouds to the distance from the observer to the horizon line (Fig. 6) is shown in the table 1.

Table 1

The ratio of the height of the clouds and the horizon

Location height, H , km	2	3	4	5	6	7	8	9	10
Horizon, L , km	159,64	195,52	225,78	252,44	276,54	298,71	319,35	338,73	357,07

As can be seen from Figure 6, the cloud base is located almost horizontally (parallel to the earth's surface) over a large extent. Many geometric and physical characteristics change with a small curvature of the sky.

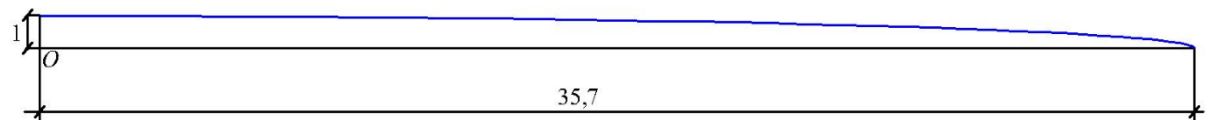


Figure 6: The real shape of the semi-clear (intermediate) sky at maximum curvature ($H = 10$ km)

For the convenience of calculations, we use the mathematical apparatus of point calculus [11-15].

A feature of the point calculus is the analytical description of geometric objects in the form of simple point equations and computational algorithms that are invariant with respect to parallel projection. This

allows, within the framework of affine geometry, to obtain a generalization to the multidimensional space.

The generalized equation of an ellipsoid in point form was obtained by O.A. Chernyshova [16]. Here we use this equation for a point description of the particular case of a spherical segment.

$$M_{ij} = (A - O) \cos \varphi_i \cos \beta_j + (B - O) \cos \varphi_i \sin \beta_j + (C - O) \sin \varphi_i + O. \quad (2)$$

Or in coordinate form:

$$\begin{cases} x_{ij} = (x_A - x_O) \cos \varphi_i \cos \beta_j + (x_B - x_O) \cos \varphi_i \sin \beta_j + (x_C - x_O) \sin \varphi_i + x_O; \\ y_{ij} = (y_A - y_O) \cos \varphi_i \cos \beta_j + (y_B - y_O) \cos \varphi_i \sin \beta_j + (y_C - y_O) \sin \varphi_i + y_O; \\ z_{ij} = (z_A - z_O) \cos \varphi_i \cos \beta_j + (z_B - z_O) \cos \varphi_i \sin \beta_j + (z_C - z_O) \sin \varphi_i + z_O. \end{cases} \quad (3)$$

where φ is the angular height of the current point of a circle of an arbitrary section (Fig. 7);

β_j is the horizontal angle of the current point from some fixed position (for example, north).

This point equation of a segment in the $ABCD$ simplex with two current parameters φ and β (azimuth) uniquely determines the position of the current point M_{ij} on the segment surface (Fig. 7)

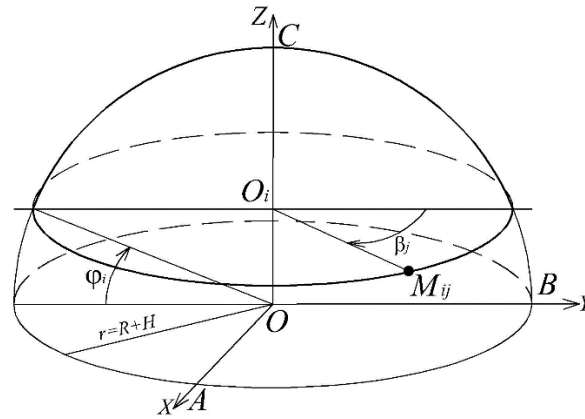


Figure 7: Parameters of a spherical segment in a simplex $AOBC$

The visualization of the obtained point equation (3) is carried out in the Maple environment in the following ranges: $\beta = 0 \dots 2\pi$, $\varphi = \arcsin\left(1 - \frac{H}{r}\right) \dots \frac{\pi}{2}$.

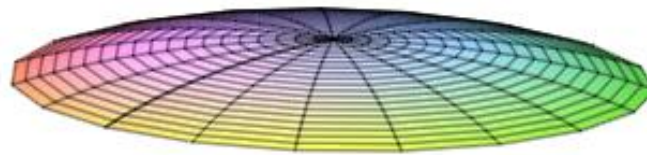


Figure 8: Visualization of spherical segment scanning points in one of the computer algebra systems (scanning points are located at the intersection of parallels and meridians)

3. Method for determining the main parameters of outdoor lighting

The luminous flux in the center of the spherical segment from its entire surface is formed within the solid angle with the apex at this point. If we use the coordinates of the obtained scanning points from equation (3), then the entire solid angle of a spherical segment can be represented as the sum of elementary solid angles (pyramids) with apex at point O_i , and the pyramid faces pass through four adjacent scanning points (Fig. 9). The base of the pyramids is an elementary surface area of a spherical segment.

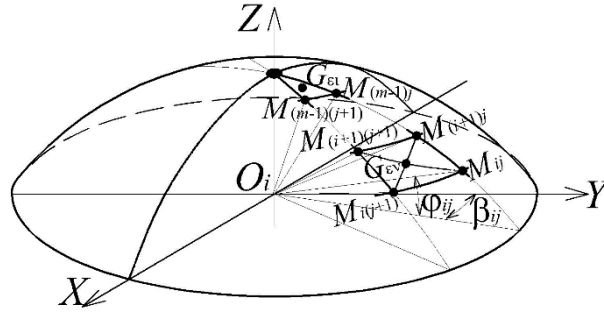


Figure 9: Formation of elementary solid angles in a spherical segment of the sky

We can assume that within an elementary solid angle (elementary pyramid), the luminance of the sky is constant, and its value corresponds to the luminance value in the direction from the center of the spherical segment to the center of elementary pyramid base gravity (we will assume that for an elementary quadrangle - the middle of one of the diagonals).

Then the coordinates of the center of gravity for the quadrangular element:

$$G_{ev} = \frac{M_{ij} + M_{(i+1)(j+1)}}{2}; \quad (4)$$

$$x_{ev}^G = \frac{x_{ij} + x_{(i+1)(j+1)}}{2}; \quad y_{ev}^G = \frac{y_{ij} + y_{(i+1)(j+1)}}{2}; \quad z_{ev}^G = \frac{z_{ij} + z_{(i+1)(j+1)}}{2}; \quad (5)$$

for triangular element:

$$G_{el} = \frac{M_{(m-1)j} + M_{(m-1)(j+1)} + C}{3}; \quad (6)$$

$$\begin{cases} x_{el}^G = \frac{x_{(m-1)j} + x_{(m-1)(j+1)} + x_C}{3} \\ y_{el}^G = \frac{y_{(m-1)j} + y_{(m-1)(j+1)} + y_C}{3} \\ z_{el}^G = \frac{z_{(m-1)j} + z_{(m-1)(j+1)} + z_C}{3} \end{cases} \quad (7)$$

The horizontal illumination in the center of the spherical segment, ΔE_{kl} , from a section of the sky within the framework of an elementary quadrangular pyramid is determined by the formula:

$$\Delta E_{ev} = L_z g_{ev}^G \Delta \sigma_{ev}^G \cos \gamma, \quad (8)$$

where L_z is the luminance of the sky at the zenith, cd / m^2 ;

g_{ev}^G is the distribution of relative luminance over the sky [9, 17].

To determine this parameter, one can use the proposal of Gillete G. Pe., Treado S. [18], according to which the luminance of the semi-clear (intermediate) sky $L_{S/I}$ is determined by the following formula:

$$L_{S/I} = L_C t + L_{CS} (1 - t), \quad (9)$$

where L_C and L_{CS} are the luminance at a given point in the sky, respectively, for a clear and cloudy sky, cd/m^2 ;

t is the cloud dependent parameter.

γ – the angle between the normal to the base of the elementary pyramid and the axis of the solid angle (Fig. 12).

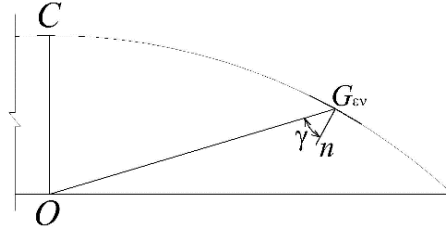


Figure 12: The angle between the normal to the base of the pyramid and the axis of the solid angle

An effective parameter that can be used to study the light climate and develop light-climatic maps is the average spherical illumination, which most fully reflects the light resources of a given area. It takes into account the reflected component from the earth's surface. Direct accounting of this component when using horizontal illumination is impossible.

Elementary average spherical illumination in the center of a spherical segment $\Delta E_{\epsilon V}^{4\pi}$, within an elementary solid angle is determined by the following formula [20]:

$$\Delta E_{\epsilon V}^{4\pi} = 0,25 g_{\epsilon V} L_z \Delta \omega_{\epsilon V}, \quad (12)$$

where $\Delta \omega_{\epsilon V}$ is the elementary solid angle.

The solid angle is determined by the following formula [21]:

$$\Delta \omega_{\epsilon V} = \left(\sum_{\lambda=1}^p A_{\lambda, \lambda+1} \right) - 2\pi, \quad (13)$$

where p is the number of faces of an elementary pyramid;

$A_{\lambda, \lambda+1}$ is the value of the internal dihedral angle between the planes that pass through the center of the spherical segment and the λ -th and $\lambda+1$ -th faces of the elementary pyramid (Fig. 13). In determining this angle, a technique developed in point calculation is used [17].

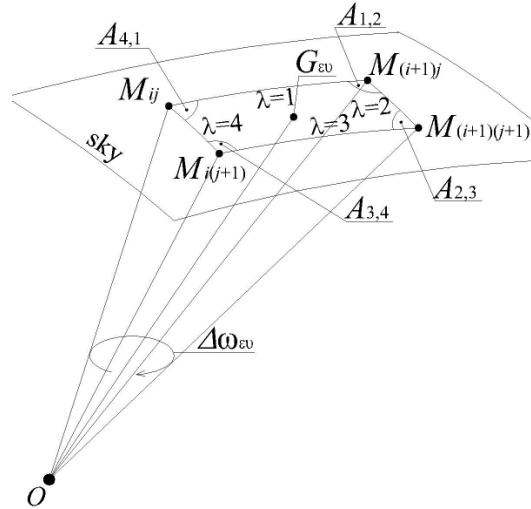


Figure 13: Scheme for determining the value of the elementary solid angle

4. Conclusion

In this paper, we propose and substantiate the use of a geometric model of the sky in the form of a spherical segment with a standard distribution of the semi-clear sky luminance (intermediate). At the same time, the following results were obtained, which have scientific novelty and practical value:

1. A geometric model of a semi-clear sky has been constructed, which is distinguished by the fact that instead of a spherical model, it is proposed to use a model in the form of a spherical segment. The segment is at the level of the cloud base and is bounded from below by a plane passing through the observation point and the visible horizon line, which better corresponds to reality.

2. The distribution of luminance over the sky has been clarified, at which it is proposed to use cloudiness in fractions of a unit as the cloudiness coefficient. It was adopted on the basis of long-term observations at meteorological stations instead of the ratio of illumination under given cloudiness conditions to illumination with ideal atmospheric transparency, which is usually used in European standards.

3. The method for determining the main parameters of outdoor lighting has been improved: horizontal and average spherical illumination, taking into account the refined geometric model of the semi-clear sky luminance distribution.

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