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EVALUATION OF ILLUMINATION QUALITY BASED ON SPATIAL-ANGULAR LUMINANCE DISTRIBUTION

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ABSTRACT

A new approach to the formulation of an illumination quality criterion based on an analysis of spatial-angular luminance distribution and of the properties of human sight is considered in this article. As part of the research, an experimental installation was developed to determine comfort and discomfort areas, which are inseparable from an assessment of illumination quality. A method for computer simulation of spatial-angular luminance distribution, based on local evaluations Monte-Carlo method is shown, which in future can facilitate moving from a preset illuminance distribution simulation to a preset quality simulation.

Keywords: local evaluations of Monte-Carlo method, spatial-angular luminance distribution, discomfort, illumination quality criterion

1. INTRODUCTION

The development of computer facilities and mathematical simulation methods has performed a real revolution in design of illumination installations (II). At the end turn of the twenty-first century, exhausting engineering calculations gave way to II computer simulation. These made it possible not only to design according to preset normalised quantitative data, but also to see a "photorealistic" picture of an installation, which was not yet in existence. On the whole, II design to match preset quantitative characteristics has been achieved in today's illumination practice, but designing to preset quality characteristics is and idea not as developed for today's lighting community. Besides, currently formulated quality characteristics have some key disadvantages. In a real engineering practice, a quality indicator is only expressed when calculating an integrated discomfort index *UGR*. If at the beginning of II simulation methods and software development, such a situation was natural, with the emergence of new methods [1] of the global illumination equation (GIE) simulation [2], totally new opportunities arise, not just for illuminance distribution calculation in a diffuse approximation but for the calculation of spatial-angular luminance distribution.

This allows to once again raise the question of an illumination quality index and of II design according to preset quality indices.

2. SIMULATION OF SPATIAL-ANGULAR LUMINANCE DISTRIBUTION USING LOCAL EVALUATIONS OF MONTE-CARLO METHOD

Modern lighting practice and normalized standards have grown out of the possibility to simulate illuminance taking into account multiple reflections, and out of the possibility to simulate luminance for direct light only without accounting for reflections. Based on this assumption, only in external illumination, and in particular in architectural and road illumination, the luminance characteristic as perceived by the human eye is normalised. One should notice that the *DIALux* and *Relux* programs generally used for II design, simulate illuminance distribution in the diffuse approximation.

With such an approach, the finite elements method simulates the luminous emittance equation [9], which is a GIE consequence [2] in the diffuse approximation.

GIE is an integral equation of the second kind

$$L(\mathbf{r},\hat{\mathbf{l}}) = L_0(\mathbf{r},\hat{\mathbf{l}}) + \\ + \frac{1}{\pi}\int L(\mathbf{r},\hat{\mathbf{l}}')\sigma(\mathbf{r};\hat{\mathbf{l}},\hat{\mathbf{l}}')\left|(\hat{\mathbf{N}},\hat{\mathbf{l}}')\right| d\hat{\mathbf{l}}', \quad (1)$$

where $L(\mathbf{r},\hat{\mathbf{l}})$ is luminance in $\mathbf{r}$ point in direction $\hat{\mathbf{l}}$, $\sigma(\mathbf{r};\hat{\mathbf{l}},\hat{\mathbf{l}}')$ is bidirectional reflection function (reflection or transmission), L_0 is direct luminance component, directly from sources, $\hat{\mathbf{N}}$ is normal in $\mathbf{r}$ point to a scene surface element.

It should be noted that at present, a new software product *DIALux Evo*, the cornerstone of which is the GIE simulation based on photon cards [10], and this fact allows simulating spatial-angular luminance distribution. However *DIALux Evo* has not found its level in engineering practice yet.

Within this article, we propose to apply local evaluations of the Monte-Carlo method for GIE calculation. The local evaluations method traces its roots to atomic physics [11] and continues its development in optics of the atmosphere and ocean [12]. GIE can be written down as a space integral and expanded into Neumann series, every term of which can be represented as a certain multiple space integral. Each term of the latter can be approximately presented as a random node quadrature, i.e. Monte-Carlo method.

After some transformations, the obtained expansion can be written down as follows [1]:

$$L(\mathbf{r},\hat{\mathbf{l}}) = L_0(\mathbf{r},\hat{\mathbf{l}}) + \\ + \frac{1}{N}\sum_{i=1}^{N}\left(\frac{1}{\pi}\frac{L_0(\mathbf{r}_{1i},\hat{\mathbf{l}}_{1i})}{p_1(\mathbf{r}_{1i},\hat{\mathbf{l}}_{1i})}\frac{\sigma(\mathbf{r};\hat{\mathbf{l}}_{1i},\hat{\mathbf{l}})G(\mathbf{r}_1,\mathbf{r})}{p_2(\mathbf{r}_{1i},\hat{\mathbf{l}}_{1i}\to\mathbf{r},\hat{\mathbf{l}})} + \right. \\ + \frac{1}{\pi^2}\frac{L_0(\mathbf{r}_{1i},\hat{\mathbf{l}}_{1i})}{p_1(\mathbf{r}_{1i},\hat{\mathbf{l}}_{1i})}\frac{\sigma(\mathbf{r}_{2i};\hat{\mathbf{l}}_{1i},\hat{\mathbf{l}}_{2i})G(\mathbf{r}_{1i},\mathbf{r}_{2i})}{p_2(\mathbf{r}_{1i},\hat{\mathbf{l}}_{1i}\to\mathbf{r}_{2i},\hat{\mathbf{l}}_{2i})}\times \\ \left.\times\frac{\sigma(\mathbf{r};\hat{\mathbf{l}}_{2i},\hat{\mathbf{l}})G(\mathbf{r}_{2i},\mathbf{r})}{p_2(\mathbf{r}_{2i},\hat{\mathbf{l}}_{2i}\to\mathbf{r},\hat{\mathbf{l}})} + \ldots\right), \quad (2)$$

where $p_1(\mathbf{r}_{1i},\hat{\mathbf{l}}_{1i})$, $p_2(\mathbf{r}_{1i},\hat{\mathbf{l}}_{1i}\to\mathbf{r},\hat{\mathbf{l}})$ are initial and transitional probability densities determining position of random nodes [12].

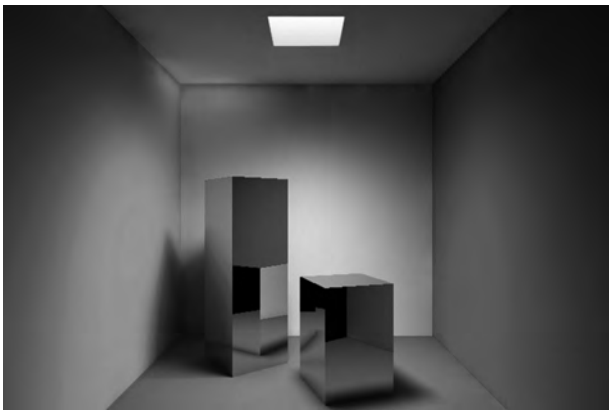


Fig. 1. Example of visualization of the space-angular luminance distribution by local estimates of the Monte Carlo method for the *Cornell Boxes* reference scene

As $p_2(\mathbf{r}_{1i},\hat{\mathbf{l}}_{1i}\to\mathbf{r},\hat{\mathbf{l}})$ is only determined by two sequential random nodes, the expression can be interpreted as a Markov's chain. As a result of creating the Markov's chain, the transition nucleus for studied points $\mathbf{r},\hat{\mathbf{l}}$ at each chain stage can be estimated. Accumulating the statistics will directly obtain the luminance at preset points along the preset directions [1]. Such an evaluation can be called a local evaluation similarly to evaluations in atmospheric optics [12].

Let us formulate an algorithm of the local evaluation. In the first stage, the studied points and directions $\mathbf{r},\hat{\mathbf{l}}$ in a scene are recorded. Then a light source is randomly selected and an arbitrary direction of the ray output from the source is determined. Source sampling with a probability proportional to its luminous flux, and the choice of direction according to the source of luminance distribution, or to the luminous intensity curve will be most effective. After this, the obtained ray is traced until crossing with an object. Further, for each of the studied points, the GIE nucleus is calculated and the statistics collected. After the statistics have been accumulated, averaged and normalised, we directly obtain luminance in the preset points along the preset directions. And in this method, a diffuse-directed reflection model can be used, for example, Phong's model [13].

For the first time, an algorithm similar to the local evaluations, was formulated in [14] as applied to visualisation in computer graphics within a phenomenological approach and was named *Instant Radiosity*. The absence of a strict mathematical argumentation for the computer graphics algorithm is not a disadvantage in most cases as the main ob-

jective of this is a "photorealistic" visualization but not exact luminance values. As to the light engineering component, the situation different: it is important here to have unbiased values of luminance for its analysis. The algorithm proposed in [14] was earlier considered in [11], and its mathematical argumentation is given in [1]. Fig. 1 shows an example of luminance distribution calculation in the *Cornell Boxes* master scene.

Thus, local evaluations allow simulating direct luminance in a preset point and along a preset direction.

Knowing luminance distribution at each point of the illumination scene, one can calculate any characteristic of the light field. Most interesting is the calculation of a value characterising illumination quality according to a preset level of visual work, and corresponding to the ideas of light design for scene illumination. Deriving such a criterion would allow computerising the optimisation of the lighting installation calculation. Even better if the program prompts a set of optimum illumination versions giving the designer a final choice of the light environment in the scene.

2. CRITERION OF ILLUMINATION QUALITY

The results of our research allow distinguishing between several factors influencing visual discomfort, and hence illumination quality as a whole:

- spatial-angular luminance distribution;
- visual adaptation;
- spectral composition of the light source radiation;
- exposition time.

It follows from the experiments that the first two factors have the most significant impact, whereas influence of the spectral composition of the light source radiation and of the exposition time require separate research.

There is no definition of illumination quality in the modern edition of the Dictionary of the International Illumination Commission. Therefore, we propose our own: *illumination can be considered high quality, if it increases visual working capacity of a person and does not interfere with compliting the tasks set within an illumination scene*.

Current quantitative illumination characteristics are as a rule normalised as one digit. In an ideal scenario, quality characteristics should be also normalised as separate digits.

An objective was set for this research project: to formulate illumination quality evaluation as one integral value for an arbitrary illumination scene with a known luminance distribution for each point in space in each direction.

Discomfort is influenced by the relation of the source luminance to the background luminance [6], i.e. by contrast. And there is a contrast threshold, after which a feeling of discomfort appears. In our opinion, it is exactly the relationship of the contrast to the threshold exactly can serve as a criterion of illumination quality. In the event of continuous a spatial-angular luminance distribution over the illumination scene, a natural contrast generalisation is the relation of the luminance distribution gradient over the observation field to an average luminance over the luminance field. With an increase of the gradient, a boundary between the glare source and the background becomes more circumscribed, and illumination quality decreases respectively. Further, it can be assumed that a change in luminance direction does not influence illumination quality, and therefore we take into consideration an absolute gradient value. Having selected a space point within the scene (room) and an observation direction, one can determine generalised contrast in the scene point:

$$K(x,y)=\frac{\left|\mathrm{grad}L(x,y)\right|}{\bar{L}},$$
$$\bar{L}=\frac{1}{A}\int_{(A)}L(x,y)p(x,y)dxdy,\ \ A=\int_{(A)}dxdy, \tag{3}$$

where x, y are co-ordinates of a point on the scene projection, L is luminance in the point of the observation direction, $\bar{L}$ is average luminance over the vision field, $p(x, y)$ is a weight function accounting for various contributions to the eye's reaction of the points located in the middle of the visual field and on the periphery, because the density of cones is greatest at the visual axis [7].

Coordinates x, y in a synthesised image are directly connected with the sighting direction $\hat{\mathbf{l}}$ for spatial-angular luminance distribution $L(\mathbf{r},\hat{\mathbf{l}})$ from when assigning a sighting point of the scene, or a specific point in light design, which is the same, as well as the camera focus of the scene visualization.

Fig. 2. Example of setting the weight coefficient *p* for different fields of view

In this regard, *A* can be interpreted as a visualisation frame area, or as solid angle of the camera's visual field.

The distribution of cones over the retina can be considered proportional to 1/θ2, where θ is the angle of sight [8]. Respectively, the added function *p* should be proportional to this value, or can be preset in a tabular way, for example as shown in Fig. 2.

As *Q*, the criterion of illumination quality, we use generalised contrast $K(x, y)$ weight-averaged over the field (equation):

$$Q = \frac{1}{AK_{thr}} \int K(x,y)\, p(x,y) dxdy, \qquad (4)$$

where K_{thr} is the threshold contrast value.

It should be noted that in most practical lighting tasks, we are concerned with illumination not of the whole scene but only of some of its parts. So in indoor illumination, operation surfaces illuminance is normalized, but not illuminance of passages. When illuminating a sports ground, primarily its playing field should be illuminated. Moreover, designers often form areas of accenting illumination to create some light rhythm in the illumination of the scene. Thus one more additional weight coefficient h ($0 \le h(x, y) \le 1$), should be introduced. This coefficient takes into consideration lighting tasks, and it is equal to 1 in the working area and to 0 for points insignificant for illumination quality. Selection of coefficient $h(x, y)$ values corresponds to algorithms of fuzzy logics [15]. An example of $h(x, y)$ coefficient set is briefly shown in Fig. 3.

Hence, expression for the quality criterion calculation will be as follows:

$$Q = \frac{1}{AK_{thr}} \int K(x,y)\, p(x,y) h(x,y) dxdy. \qquad (5)$$

The obtained expression can be used for the evaluation of illumination quality by one digit, if the evaluation is carried out by means of the software, when luminance distribution for all scene points is known in any direction.

It should be noted that the quality criterion undoubtedly needs an experimental calibration test, however in our opinion, there is no necessity of its ultraprecise determination: first, visual perception dispersion reaches scores of percents, and secondly, this criterion is only necessary for optimizing the choice of the illumination design model giving a final decision the light designer.

3. EXPERIMENTAL DETERMINATION OF DISCOMFORT LUMINANCE AT THE COMFORT – DISCOMFORT BOUNDARY

Illumination quality characteristics are directly connected with the observer determining feelings of comfort or discomfort. And the observer's evaluation is subjective and can change from one observer to another in a very wide range. It is commonly supposed that discomfort glare is an unpleasant sensation in case of non-uniform luminance distribution or high level luminance in the visual fild $L(\mathbf{r}, \hat{\mathbf{l}})$. The glare phenomenon makes difficult reading indications of devices. It degrades visibility of the observed objects and causes a premature fatigue of the visual analyzer. In this respect, the added criterion *Q* allows estimating illumination discomfort in a scene from a stable scenery spot but discomfort determination requires a study of K_{thr}. – characteristics of the human eyes threshold.

As part of this research, at the Light and Engineering Chair of the Moscow Power Institute NRU, a study was conducted to estimate the discomfort sensation caused by a glare source in the observer's field of vision. Luckiesh and Guth's experiment [3] from 1949 on finding a boundary value of the discomfort glare was used as a basis for this experiment,. During the experiment, dependences of this parameter on the main factors were revealed.

Within Luckiesh and Guth's experiment, an expanded visual field of uniform luminance was si-

Fig. 3. Example of determining the weight coefficient *h*, taking into account the lighting task

mulated using two-thirds of an 80-inch (2 m) photometric sphere with a lamp located near its centre to provide a uniform illuminance field. Light sources were located behind round openings in the sphere surface. These openings were provided for sources of a bright light. The observer was located on a chair, so that his head was exactly in the centre of the sphere.

An evaluation of the glare sensation was made at a short-term emergence of the source in the observer's field of vision under the condition of a uniform background luminance distribution. Background luminance was considered to be equal to adaptation luminance. The experiment included cycles of three one-second "switched on" periods with intervals equal to 1 between them with a subsequent five-second pause between the cycles. The observers themselves determined the number of experiment cycles sufficient for a luminance evaluation *in the visual field at the border between comfort and discomfort (BCD).*

In total, fifty observers took part in the experiment. They adjusted the initial luminance to determine their own BCD criterion.

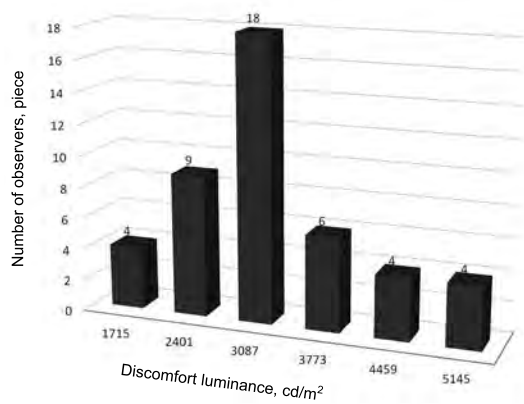
In order to determine the discomfort glare boundary value and its dependences on the main factors, Luckiesh and Guth performed one more series of experiments. In this series, background luminance values (1, 10 and 100 foot lambert (1 foot lambert = 10.764 lx)), angular size of the light source (in an interval from 0.0001 to 0.126 sr), and light source position were changed (in an interval from 0 to 100° relative to the vision line along vertical, horizontal, and diagonal). Only ten observers participated in these experiments. The dependence of BCD luminance dependence, location and number of glare sources in the observer field of vision was also determined.

According to the results of the Luckiesh and Guth experiment, the BCD luminance value was equal to 3103 cd/m^2, if adaptation luminance was – 31.4cd/m^2, and the light source diameter was equal to 3.76 cm. The light source was placed on the observers' vision line at a distance of 1 m from the observer. Fig. 4 shows BCD luminance value distribution depending on the observer number.

With pressing concerns for energy saving and energy efficiency, light emitting diodes and lighting devices based on LEDs become the main sources of light. Light emitting diode (LED) illumination is applied everywhere, and discomfort from glare of small size light sources is a topical problem [4].

Besides, the small size and various optical characteristics of LEDs and LED matrices allow simulating glare light sources of any size and configuration using imitation of light spots on a desktop, or blinding headlights of an oncoming vehicle.

For more advanced and modern studies of BCD luminance, an experimental installation was developed at the Lighting Engineering Chair of the Mos-



Fig, 4. Distribution of brightness values of the GCD ("standard BCD brightness").

Fig. 5. Experimental installation

cow Power Institute. As the base of the installation, a metal sheet painted with white powder paint was used. On this sheet, plates on which cards of LED's various location were mounted. At the sheet centre, a round card with three LEDs of 0.3 W was placed. Around them, larger rectangular cards imitating glare light sources were mounted. Chromatic temperature of the installed LEDs was equal to 5000 K. Switching on the cards in various modes was performed from a control unit, by means of which light source luminous fluxes could be adjusted. The experimental installation was located at a height of 0.75 m from the floor, so that the central card was at the observer's eyes level. The experimental installation is shown in Fig. 5.

In process of developing and improving the experimental technique, a need to instal an opaque cloth for a greater light diffusion was revealed. In order to change the chromaticity towards a lower chromatic temperature, the LEE Filters 204 full C.T *ORANGE* filter was installed. And to simulate one light source of 3.76 cm diameter, a diffusion light filter was applied. General illumination and respectively, background luminance indoors, was created using six controlled built-in LED luminaires. The installation was controlled by means of toggle-switches, and for each light source (composite or single-unit) its own switch was provided for. Calibration of the experimental installation was made using luminance metre *Konika Minolta LS-110*.

To develop the discomfort scale, five main Hopkinson's criteria were used [5]: noticeable, acceptable, uncomfortable, inconveniently and intolerable. In the process of training the sensation determination technique, it was revealed that the interpretation for the participants was unevident, and some criteria were determined as an interval of luminance values.

Therefore, after researching various scales, selection of optimum easily understood definitions of each criterion, together with carrying out visual work during the experiment, the following scale of discomfort was selected: hardly noticeable; indifferently; acceptable; uncomfortable; inconveniently; insufferably.

Luminance of the glare source was first adjusted by the protocol administrator, then by the participant using a built-in light controller. The experiment's results showed that when participants were adjusting luminance there was less data scattering in comparison with the adjustment made by the administrator.

As it is not possible to adjust general illumination in the classroom from 0 to 100 %, during the experiment background luminance (adaptation luminance) was equal to 75 cd/m^2. The observer was placed on a chair in front of the installation at a distance of 1 m from it. In total, 63 answers for each criterion were obtained. Looking at the experiment results, the discomfort luminance value of 3350 cd/m^2 was obtained, which was different from the value obtained by Luckiesh and Guth by 300 cd/m^2 upward.

Such a difference in BCD luminance values was obtained due to some engineering limitations, because of which it was impossible to reproduce completely the Luckiesh and Guth's experiment conditions in the experimental environment of the existing installation. The main reasons of the difference in results are as follows:

• Background luminance in the MEI installation was almost twice as high as that declared in the

Luckiesh and Guth's experiment: 75 and 34 cd/m^2 respectively;

• The assumed chromatic temperature of the thermal light sources used in the Luckiesh and Guth's experiment (2700–3000 K) considerably differs from chromatic temperature of the LEDs used in the MEI installation (5000 K);

• In Luckiesh and Guth's installation, one test light source was used, and in the MEI installation, light sources of different sizes were formed using single-unit LED of various arrangements.

Based on the performed experiment, we have managed to determine that radiation chromaticity influences the BCD luminance value. BCD luminance also depends on a number and configuration of glare light sources in the observer's field of vision. During the primary experiment, only three LEDs were merged into one (light source diameter = 3.76 cm) at high luminance values corresponding to painful ("intolerable") sensations, and when BCD luminance determining, they could not been perceived by the eye as a source equivalent to one light source of a bigger diameter.

After the experimental installation was upgraded in response to the results of the initial study, all BCD dependences qualitatively coincided with the Luckiesh and Guth's, which confirms that the developed technique was correct. In our opinion, a numerical coincidence cannot be achieved: as it follows from the description of measured results, to achieve this it would have been necessary to completely reproduce their installation, but there were no need to do this.

The original study carried out all measurements using an incandescent lamp, whereas this experiment used much more modern and current LED sources.

CONCLUSION

Through this research, a new integrated approach to the study and determination of a new illumination quality criterion is proposed, which is based on the spatial-angular luminance distribution. A transition from designing according to a preset illuminance distribution, to designing according to a preset quality is already an obvious trend. This transition has become possible due to the development of the computer facilities and mathematical methods of GIE simulation. As a result, it is impossible to formulate a new quality criterion without experimental research because of the lack of a physically appropriate model of luminance perception by the human eye.

As a result of this study, an algorithm of luminance spatial-angular distribution calculation was proposed and implemented, taking into account multiple specular reflections, which is essential when determining discomfort in an illumination scene. An experimental installation for studying discomfort was created and the experiments performed by Luckiesh and Guth were replicated.

The proposed approach for the formulation of a quality criterion based on an integral evaluation of spatial-angular luminance distribution is a good starting point to develop a program package of II design according to a preset illumination quality.

REFERENCES

1. Budak, V., Zheltov, V., Notfulin, R., Chembaev, V. Relation of Instant Radiosity Method with Local Estimations of Monte Carlo Method // WSCG. 2016, pp. 189–197.

2. Kajiya, J.T. The rendering equation // Computer Graphics (Proc. SIGGRAPH'86). 1986, V. 20, #. 4, pp. 143–150.

3. Luckiesh, M., Guth, S.K. Brightness in the visual field at borderline between comfort and discomfort // Illuminating Engineering. 1949, V.44, #. 11, pp. 650–670.

4. Wout Van Bommel, V. Lighting Tomorrow: What's Hot? // Light & Engineering, 2010, #2, V.18, pp.5–9.

5. Hopkinson, R.G. Evaluation of Glare // Illuminating Engineering. 1957.V. 52, #. 6, pp. 305–321.

6. Scheir, G.H., Hanselaer, P., Bracke, P., Deconinck, G., Ryckaert, W. Calculation of the Unified Glare Rating based on luminance maps for uniform and non-uniform light sources // Building and Environment. 2015, V.84, pp. 60–67.

7. Lombardo, M., Lombardo, G., Lomoriello, D.S., Ducoli, P., Stirpe, M., Serrao, S. Interocular symmetry of parafoveal photoreceptor cone density distribution // Retina. 2013, V. 33, #8, pp. 1640–1649.

8. Larson, G.W. et al. A visibility matching tone reproduction operator for high dynamic range scenes // IEEE Transactions on Visualization and Computer Graphics.1997, V.3, # 4, pp. 291–306.

9. Goral, C., Torrance, K.E., Greenberg, D.P., Battaile, B. Modeling the interaction of light between diffuse surfaces // Computer Graphics. 1984. V. 18, No. 3, pp. 213–222.

10. Christensen, N. J., Jensen, H. W. A Practical Guide to Global illumination and Photon Maps // Proc. SIGGRAPH, 2000.

11. Kalos, M.H. On the Estimation of Flux at a Point by Monte Carlo // Nuclear Science and Engineering. 1963, V.16, No.1, pp. 111–117.

12. Monte-Carlo method in atmospheric optics / Under the editorship of G.I. Marchuk. Novosibirsk: Nauka, 1976.

13. Phong Bui Tuong. Illumination for Computer Generated Pictures // CACM. 1975, Vol. 18, No. 6, pp. 311–317.

14. Keller, A. Instant radiosity // Proc. SIGGRAPH, 1997. P. 49–56.

15. Batyrshin I.Z. Main operations of fuzzy logic and their generalisations. Kazan: Otechestvo, 2001, 102 p.

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