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Optimization based on reconstruction of volume scattering medium parameters

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ABSTRACT

Lighting design or stray light simulation of imaging or non-imaging optical systems requires a precise specification of the optical properties of the scattering materials and one of the ways of the proper specification is the Bidirectional Scattering Distribution Function (BSDF). Although, it is possible to obtain data about the optical properties of the sample for example by measurement of the BSDF, but it is difficult to extract the properties of the sample components (BSDF of the sample boundary, parameters of volume scattering, etc.). In such cases, it is required to reconstruct these properties. For this operation, there are many methods, like the reconstruction of the BSDF of the microrelief, but they not applicable in cases when the volume scattering is used. Authors have developed a method for optimization of the volume scattering media parameters, which shows good agreement with the measurements of the sample BSDF.

Keywords: BSDF, BSDF measurements, BSDF reconstruction, volume scattering, Mie scattering, Rayleigh scattering

1. INTRODUCTION

Nowadays, there are a lot of electronic devices with complex optical systems, wherein elements with complicated spatial light intensity distribution are used. Such electronic devices include, for example, LGP (light-guiding plate) systems for LCDs, cars dashboards, lighting fixtures, etc. The quality and technical parameters of that devices get better day by the day. Along with the quality their technical complexity and requirements are increasing. A lot of problems arise for developers of such projects. One of the major problems is the physically accurate modelling of optical systems with the light scattering. Errors in the light simulation could provide incorrect behavior of the electronic device as a whole, and it could lead to a deviation from the technical requirements. It is also important that speed of the modelling and calculations should be very fast, because in most cases developers have time limits and they need to observe a lot of various test samples, to discuss results and make optimization for the whole system that is why quickness and correctness of the lighting simulation is very important.

Generally speaking, for an accurate modelling it is important to have the accurate optical properties of the scattering material. Currently, one way to describe the optical property of scattering materials is to use the Bidirectional Scattering Distribution Function (BSDF). This function quantifies the angular dependence of the diffuse scattering by the surface. The BSDF has a very difficult definition. In brief, it is a superset and generalization of two functions: Bidirectional Reflectance Distribution Function (BRDF) and Bidirectional Transmittance Distribution Function (BTDF). The key point of all that functions could be described as a black box with the input data of incident ray and reflected or transmitted ray at a given point of the surface. The output data of this black box is the value of ratio between incoming and outgoing light energy for the both angles, or it can also be defined as ratio between the radiance of the surface (L_r) to the irradiance (E_i) on that surface.

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The light scattering appears when ray falls on the rough surface and reflects not speculary but in different directions. At present, there are many different diffuse optical materials, which consist of the rough surface or the volume scattering or their combinations[1] (Figure 1).

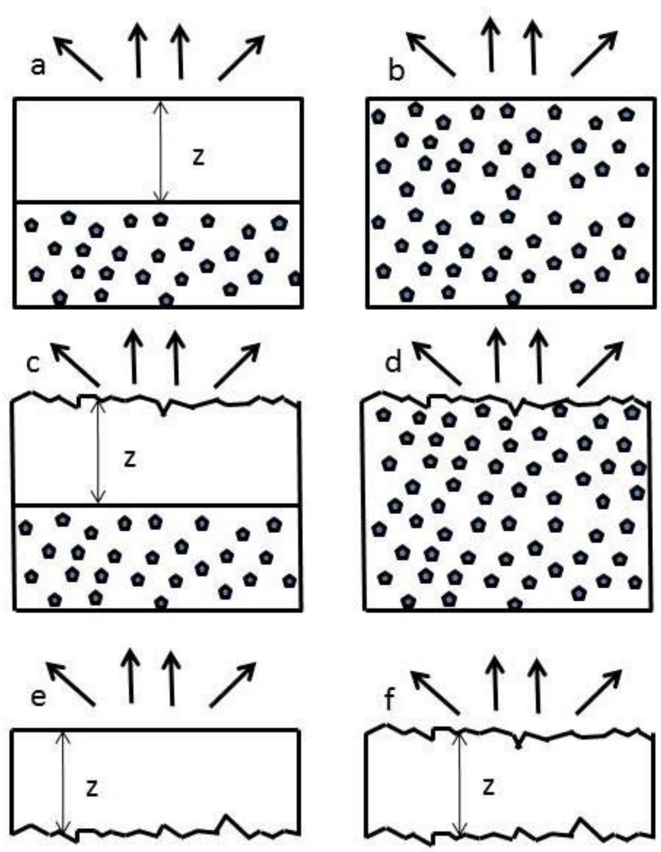


Figure 1. Schematic of 6 types of diffusers. Light is measured above the diagrams. The layer of volume scattering is shown marked. Areas without marks are assumed to be nonscattering. Rough surface shown at c – f

In most cases, developers and designer have a material sample, for example in a form of a plane-parallel plate, but they do not know the parameters of the individual components, like parameters of the scattering medium and the roughness of boundaries. When there are tasks connected with modelling the certain component of a diffuse material, unfortunately, it becomes impossible. The main reason is that, it is incredibly difficult to specify the boundary properties and the parameters of the diffuse layer separately, i.e. to measure the BSDF of the separate components of the diffuse plate. It is possible only to measure the BSDF of the whole sample. Although, there are such cases, when the shape of the scattering material differs from the measured sample and cannot be reduced to the one sheet surface. For instance, the model of the single BSDF is not suitable when this sample is an element of a light-guiding system or a volume diffuser, and thus, multiple reflections occur either between the boundaries of the sample or between the scattering particles of the same material. For this reason, it is important to specify the optical surface properties and the parameters of the scattering layer separately. The process of determination of the optimal parameters of the medium, which previously was unknown, is called the reconstruction of the BSDF.

There are a lot of methods for the reconstruction of one of the BSDF parts – BRDF. All of them are used in computer graphics and in lighting simulations, nevertheless, they are not applicable in tasks connected with diffuse and transparent materials if there is requirement of physical accurate modelling. Also, there are effective methods for the BSDF reconstruction in scattering material with rough surface[2, 3]. However, all of them could not provide reliable results, in cases, when optical material has got not only rough surface but also a diffuse layer, in which volume scattering arises. Definitely, there are methods for volume scattering modelling, for example in Magarill et al. article [4]. That method shows good results, but there is no full description about how it really works and the method was developed only for the LightTools illumination software. In this article, authors propose own method for BSDF reconstruction for the volume scattering medium.

2. METHODS AND MODELS

There are several approaches for describing the scattering. In situations where the size of the scattering particles is comparable to the wavelength of the light, rather than much smaller or much larger, the Mie solution is used.

Another model is Rayleigh scattering. In this case, there is an elastic scattering of light by particles much smaller than wavelength. The particles could be individual atoms or molecules. It can occur when light travels through transparent media and it can be better seen in gases. The size of a scattering particle could be defined by equation (1):

$$x = \frac{2\pi r}{\lambda} \tag{1}$$

where r is the characteristic length and λ is the wavelength.

Also, there is a Henyay-Greenstein (HG) phase function, which is widely used in the light scattering calculations. This function is convenient for some numeric calculations, because it has an analytic term and disclose to Legendre polynomials. Even more, it could provide the easy computations of an asymptotic light radiance distribution[5, 6].

The HG phase function has the following form (2):

$$p_{HG}(\mu, g) = \frac{1-g^2}{(1-2g\mu+g^2)^{3/2}},\ \mu = \cos\nu \tag{2}$$

where ν is the scattering angle, and g is the asymmetric parameter, equal to the average cosine, $\cos\nu$ over the angular distribution defined as (3):

$$\cos v = \frac{1}{2}\int_{-1}^{1} p(\mu)\mu d\mu \tag{3}$$

$$\frac{1}{2}\int_{-1}^{1} p(\mu)\mu d\mu = 1.$$

Therefore, in different situations we can use the suitable approach for volume scattering. Our algorithm consists of all of them, and an optical developer can choose one of them. In the capacity of the parameters, which might be optimized, we used size, refraction index and concentration of the scattering particles in the Mie/Rayleigh approach, or parameters of the HG phase function.

Previously, the method for the reconstruction of microrelief was published[7]. Currently, we propose a combined behavior. The algorithm consists of the next operations, which are illustrated at Figure 2:

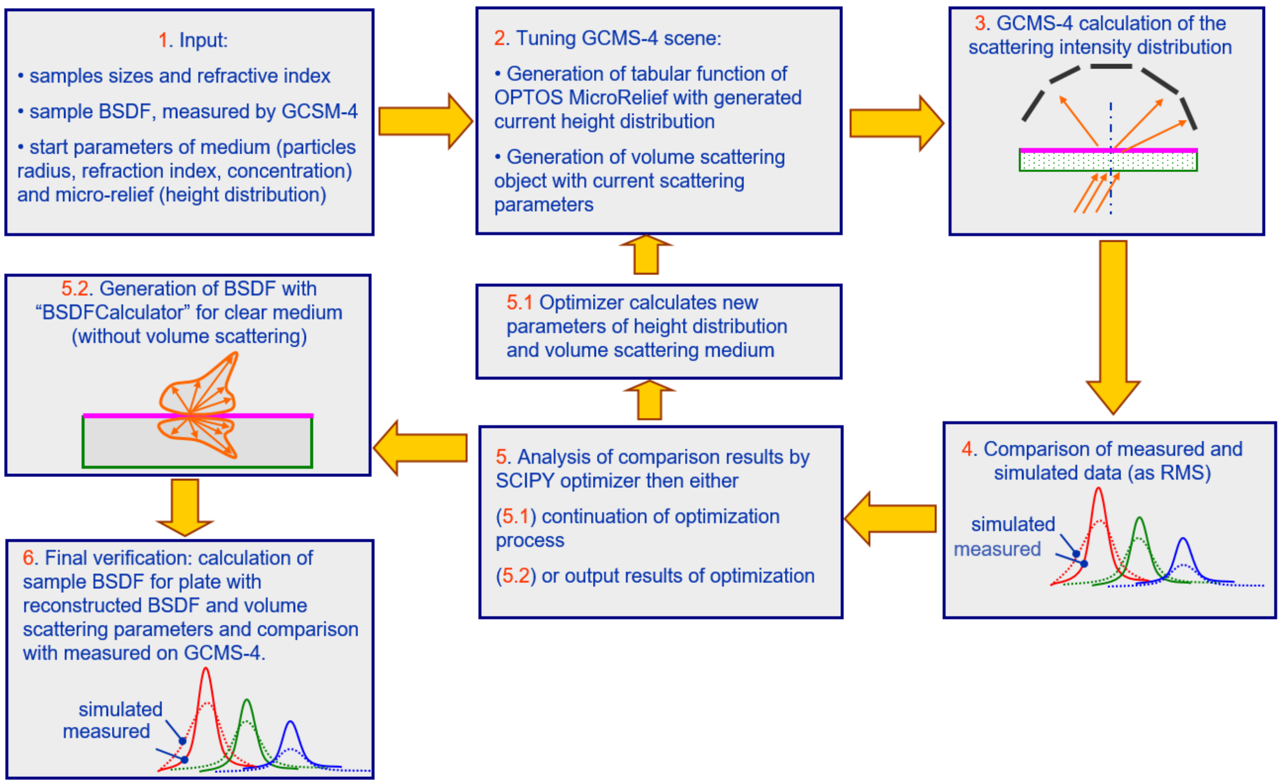


Figure 2. The general scheme of the reconstruction of parameters of the volume scattering and BSDF of the medium boundary

At first, it is need to collect all the data necessary for the simulation and optimization. The data includes parameters of the microrelief (heights distribution) of the sample boundary, which can be measured by a surface profilometer or an atomic force microscope. Next this set of data used in the optimization process is the sample BSDF. Usually the goniospectrophotometer is applied to measure the BSDF of the sample. For this task, we suggest to use GCSM-4[8, 10] or Gonio-Photometer II by "Pab Ltd"[9]. These systems are certificated and the resulting data is reliable.

Next four steps represent the optimization process consisting of the following operations:

- Preparation of the scene corresponding to the measured sample. To create microrelief the measured heights distribution is delivered to the special OPTOS MicroRelief tool[11, 12] used in the light simulations. To create volume scattering one of the models (Rayleigh, Mie or Henyay-Greenstein)[13] is created with the proper set of parameters. Initial parameter goes from the measurements or common sense conditions (parameters of the volume scattering model). Then the optimizer changes these parameters to meet the optimization goal.
- Light simulator, which performs calculation of virtual sample used in GCSM-4 or Gonio-Photometer II device. The simulation results are wholly agreed measurement results and can be easy compared.
- Comparison of the simulated and measured results. Usually the result of the comparison is a single value of the deviation (RMS). Taking into account that results of the measurements (and the corresponding simulation) are hundreds or thousands of values, we can set the special weight for each value. For example, we can make the influence of the simulation results obtained for the orthogonal sample illumination to be more important than results the one obtained for the grazing angles.

- Analysis of the simulation results. If our RMS reached the target then we stop the optimization process and finalize the simulation results. In opposite case we have to continue the optimization process with new parameters of optimization. The optimizer determines new parameter of the volume scattering model and parameters of the microrelief (height distribution) modification. Taking into account that the height distribution of the microrelief was measured we can conclude that its BSDF is about correct from the beginning so weights of parameters of the volume scattering is much higher than weights of parameters of the microrelief modification in the optimization process. After parameter modification we cycle to the optimization procedure and go to the scene preparation.

At the end of the optimization process, we finalize our data. The finalization consists of two steps. The first is conversion of the OPTOS MicroRelief to the BSDF of the boundary of two media. Moreover, taking into account that we separated the surface from the volume scattering the conversion of the optimized microrelief to BSDF is performed for clear media of the boundary.

Finally, we fulfill verification of our optimized models with the BSDF on the boundary and scattering medium in volume. The main difference of the model for verification from the model used in the optimization process is the model of the surface scattering. The optimization process uses the OPTOS MicroRelief while the final scene uses the BSDF converted from the OPTOS MicroRelief. Taking into account that OPTOS MicroRelief uses the ray tracing approach while conversion procedure can use both ray tracing and wave solutions so some deviation between optimized and final BSDF are possible.

3. RESULTS

As stated earlier, the main goal of the process is reconstruction of scattering media properties in such manner, that it will be closely toward the real sample and it will be for one-sheet layer. We tested several problematic examples. First of all, we would like to show that methods used for the optimization of the relief scattering material are not applicable for the volume scattering. Figure 3 shows results which connected with case above. Solid line relates to measurements, dash line relates to simulation, and as it is seen, there is no agreement between the modeling and the simulation. This proves that the method of optimization microrelief should not be used in case of the volume scattering.

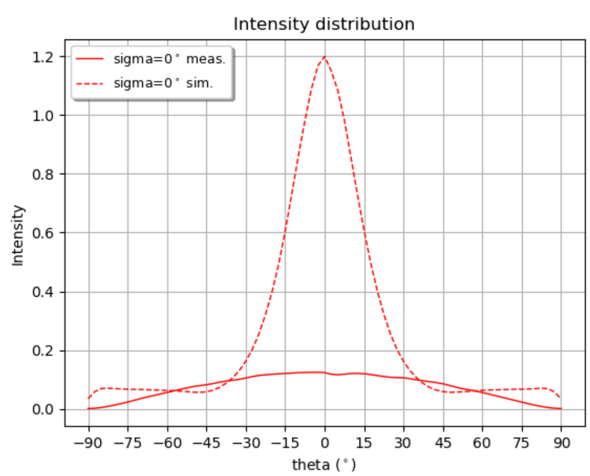
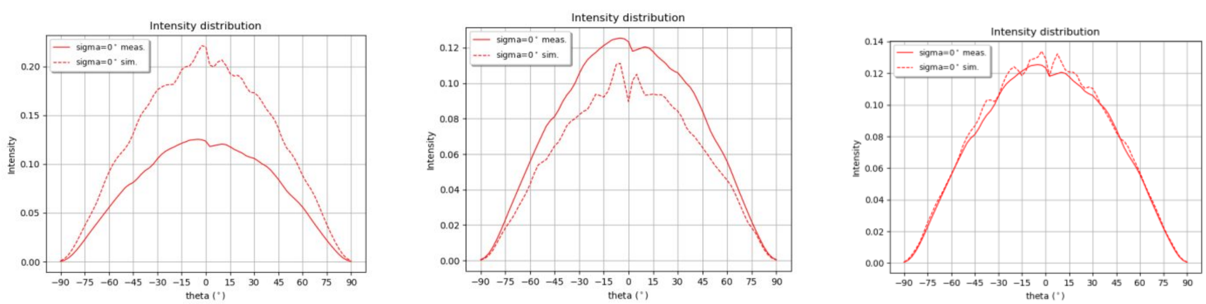


Figure 3. Slice of results of BSDF reconstruction based on microprofile fitting in volume scattering material. Solid line relates to measurement intensity, dot line to simulated intensity

The next experiment requires detailed description of whole method. The sample has size 100 x100 mm, thickness is 1 mm, the thickness of the volume scattering layer is 0.15 mm and it is positioned at the top of sample, index of refraction is 1.5 (Figure 5). We consider, that every optical developer can get this data quite easy, without use of any specific equipment and that is why it is assigned at the beginning. Also, information of the BSDF is required, thereby, the information about BTDF an BRDF from the top, and BTDF and BRDF from the bottom is needed. When these data are defined, we can continue model preparation. Parameters of optimization include the parameters of scattering agent (SA): SA particle volume concentration (PVC), SA radius, SA index of refraction and the layer parameters: layer size, refraction index (Re. and Im. Components). It is possible to choose the appropriate parameters and to set the range from minimum to maximum value and alteration step. Also at this phase, the wavelength range and count of iterations can be adjusted.

Figure 4 shows process of optimization of the volume scattering parameters.



a b c

Figure 4. Slices of the results of BSDF reconstruction based on the optimizing parameters of volume scattering material. Solid line relates to the measurement intensity, dot line to the simulated intensity, where a – the first step, b – the 15th step, c – 29th step of optimization process

For this sample (Figure 5), we suggested that Mie scattering model is the most suitable, therefore, parameters of the Mie model were optimized. For the plot shown in Figure 4a the initial value for SAPVC was 3%, minimum value was 2% and maximum value was 4%. The next parameter was SA radius: its initial value was 500 nm, minimum value was 100 nm and maximum value was 1000 nm. Also, we tried to optimize the index of refraction of the sample, with its initial value set to 1.7, minimum value set to 1.5 and maximum value set to 2.0. The last parameter was the layer size. Its initial value was 0.2 mm, minimum value was 0.1 mm and maximum value was 0.3 mm. RMS for the first step was 37.4%. When the 15th step of optimization came (Figure 4b), parameters were changed in such way: value of SAPVC became 4.09%, value of SA radius became 521.07 nm, value of index of refraction became 1.9, and value of the layer size became 0.203 mm. RMS for the 15th step was 12.7%. Actually, whole optimization process took 34 steps, but the best results of optimization were at the 29th step (Figure 4c). This step has the next parameters: value of SAPVC became 3.17%, value of SA radius became 547.93 nm, value of index of refraction became 1.93, and value of the layer size became 0.18 mm. RMS for the 29th step was 4.5%.

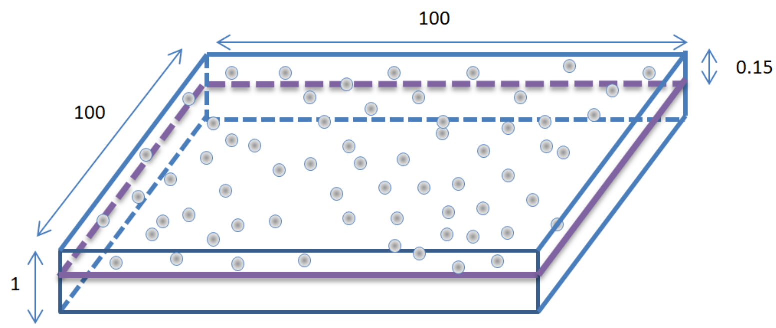


Figure 5. Scheme of model with volume scattering

This example shows us a good performance of suggested method that is why we applied that for more difficult situation, which is close to a real BSDF.

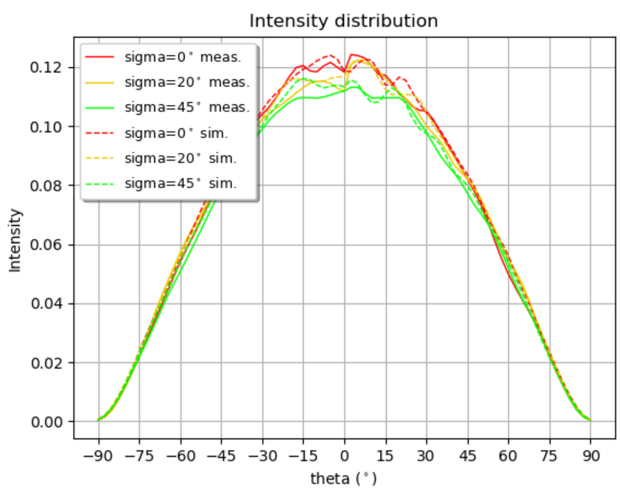


Figure 6. Slice of the results of BSDF reconstruction based on the optimizing parameters of volume scattering material for specific beam angles

Figure 6 shows the case, were there are several beam angles. Optimization process took 35 steps, and the best result RMS was about 3.5%. The process was very fast, it took about 7 minutes for all operations

.

4. CONCLUSION

Suggested method of reconstruction of the measured sample BSDF with the volume scattering material to the BSDF of the boundary and the model of the volume scattering (Rayleigh, Mie or Henyay-Greenstein) shows good agreement with the desired output. Use of this method provide fast and physically accurate reconstruction of the individual optical parameters for the samples with complex optical properties.

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REFERENCES

[1] Germer, T.A., “Bidirectional scattering distribution function measurements from volume diffusers: correction factors and associated uncertainties,” Applied optics, Vol.55, No.25 (2016). http://dx.doi.org/10.1364/AO.55.006978

[2] Nurcan, S., Serkan, E. and Aydın, Ö., “BRDF Reconstruction Using Compressive Sensing,” 21st International Conference on Computer Graphics, Visualization and Computer Vision, 88-94 (2013), ISBN 978-80-86943-74-9.

[3] Nielsen, J.B., Jensen, H.W. and Ramamoorthi, R., “On Optimal, Minimal BRDF Sampling for Reflectance Acquisition,” ACM TOG 34(6). 1-11 (2015).

[4] Magarill, S., Cassarly, W.J.,. Jenkins, D.R. and others. “Parametric Model of Volumetric Scattering,” Design and Fabrication Congress 2017 (IODC, Freeform, OFT), OSA 2017.

[5] Calabro, K.W. and Cassarly, W., “Modeling scattering in turbid media using the Gegenbauer phase function,” Proc. SPIE 9333, Biomedical Applications of Light Scattering IX, 93330F (2015); doi: 10.1117/12.2079695

[6] Kuperman-Le Bihan, Q., “Volume scattering characterization for illumination design”, Proc. SPIE 8550, Optical Systems Design 2012, 85502K (2012); doi: 10.1117/12.981995

[7] Sokolov, V.G., Zhdanov, D.D., Potemin, I.S., Bogdanov, N.N., Zhdanov, A.D. and Denisov, E.U., “Reconstruction of BSDF based on optimization of Micro-Relief normal distribution,” Proc. of 27th International Conference on Computer Graphics and Vision, 37-41. (2017),

[8] Muracami Color Research Laboratory, <http://www.mcrl.co.jp/english/index.html>

[9] Pab advanced technologies Ltd, <http://www.pab.eu/?d=gonio-photometer>

[10] Zhdanov, D.D., Potemin, I.S., Sokolov, V.G., Garbul, A.A., Voloboy, A.G. and Galaktionov, V.A., “Simulation of the BSDF measurement capabilities for various materials with GCMS-4 goniospectrophotometer,” Proceedings of 12th International Conference "Applied Optics 2016", vol. 2, 219-223 (2016).

[11] Sokolov, V.G., Zhdanov, D.D., Potemin, I.S., Garbul, A.A., Voloboy, A.G., Galaktionov, V.A. and Kirilov. N., ”Reconstruction of scattering properties of rough air-dielectric boundary,” Optical Review, 2016,23(5), 834-841, DOI: 10.1007/s10043-016-0250-6.

[12] Ershov, S.V. and Zhdanov, D.D.,“Efficient application of Optical Objects in light simulation software,” Proc. 15th International Conference on Computer Graphics and Applications - GraphiCon-2005, Russia, Novosibirsk, p. 284-288 (2005).

[13] Zhdanov, D.D. , Garbul, A.A., Potemin, I.S., Voloboy, A.G., Galaktionov, V.A., Ershov, S.V. and Sokolov, V.G.,. “Photorealistic Volume Scattering Model in the Bidirectional Stochastic Ray Tracing Problem”, Programming and Computer Software, Vol. 41, No. 5, pp. 295–301, DOI: 10.1134/S0361768815050102.(2015)