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Modelling of the exposure distribution inside heterogeneous radiosensitive layers*

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The results of computer simulations involving the stochastic method of light diffusion modelling in heterogeneous layers are presented. The spherical elementary indicatrix at the absence of front and back halation was assumed. The occurrence of the maximum of inner exposure at a certain depth inside the layer was shown which is in good agreement with experimental results obtained by Strübin, despite that earlier theoretical models showed the maximum to occur always at the front surface of the layer.

1. Introduction

The photographic light-sensitive layers are composed of microcrystals of silver halides (phase I) suspended in gelatine (phase II). The essential difference between the refractive indices in these two phases cause some scattering of the light within the layer. This scattering of actinic radiation constitutes one of the factors restricting the information capacity of the systems when used to optical recording of image information. Its influence on the precision with which the fine details are imaged can be defined both qualitatively and quantitatively by the light scattering function which is known as either the line spread function (LSF) (for the line distribution of the exposure) in the photographic structurometry, or as the point spread function (PSF) for the distribution of the exposure evoked by a point object. The light scattering function describes the dependence of the cumulative layer exposure on the distance x from the place of light incidence onto the layer. One of the physical reasons of such spreading of the optical image is just the radiation scattering inside the heterogenic medium recording the image information.

Before the experimental [1], [2] and theoretical [3] results indicating the possibility of the exposure maximum existing inside the light sensitive layer were published it had been assumed that the greatest internal illumination of the layer was at its surface and next diminished exponentially with the light penetrating in-depth the layer [4]–[6]. A schematic course of the effects occurring during the recording of the image of a thin line is shown in Fig. 1, while the LSF was

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described by the equation given below [7]

$$L_h(x) = \alpha \exp(-x/K_1) \int_0^h \exp(-z/K_2) \mathrm{d}z \tag{1}$$

where: α – constant value, x – distance from the plane of incidence of photons in the direction indicated in Fig. 1, h – layer thickness, z – depth within the layer, K_1 – parameter of scattering along the x-axis, K_2 – parameter of scattering along the z-axis. Function $L_h(x)$ means the change of the radiation intensity scattered in the x-axis direction for the layer of thickness h.

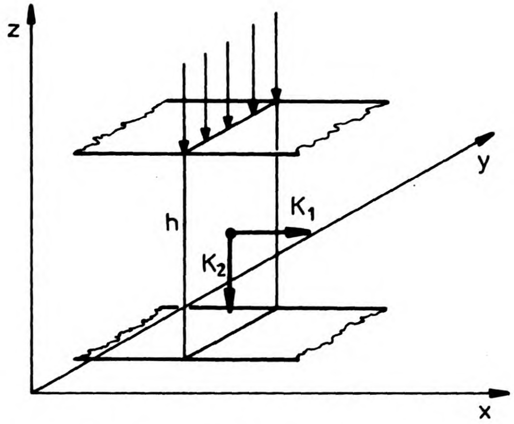

Fig. 1. Scheme of the radiation scattering effect inside the photographic layer as exemplified by exposure via a thin slit

If the graininess of the photographic layer is not sufficiently low, *i.e.*, the layer contains the silver halide crystals of diameter greater than about 0.1 μm the value of the parameter K_2 is much less than the thickness of such a layer. In such a case the integrand in Eq. (1) is approximately equal to one. The layers which show similar properties are considered to be highly scattering. In Figure 2**a** some examples of

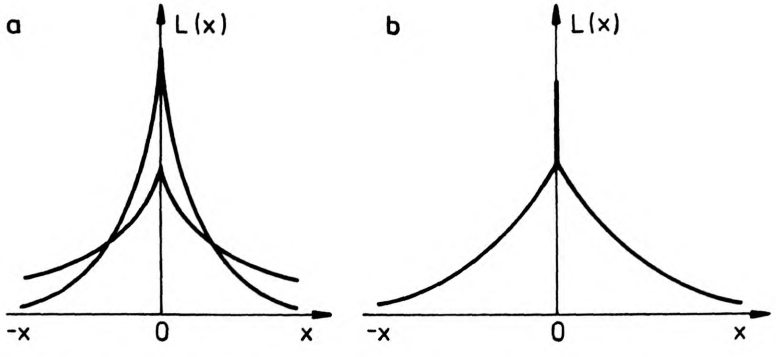

Fig. 2. LSF for the strongly scattering layers (**a**) for different values of K_1 and weakly scattering layer (**b**)

the LSF $L(x)$ for the highly scattering layers are shown for different values of the parameter k_1, whereas in Fig. 2**b** an example of the LSF of a weakly scattering layer is presented. In such a case some part of the radiation suffers from absorption without being scattered earlier and a "perfectly" acute photographic image appears being described by Dirac delta function $\delta(x)$. Then, the LSF takes the form described by Eq. (2), where parameter ρ characterizes the contribution of the unscattered radiation to the effective exposure [8]

$$L(x) = (1-\rho)/k_1 \exp(-|x|/k_1)+\rho\delta(x). \tag{2}$$

Some considerations based on the light scattering theory within the photographic layer, as well as Eq. (1) lead to the conclusion that the greatest value of the effective exposure occurs on the irradiated surface of the layer. Other considerations indicate the possibility of existence of exposure maximum at a certain depth inside the light sensitive layer. The dependence of the effective exposure H on the depth h within the layer was examined experimentally by Strübin.

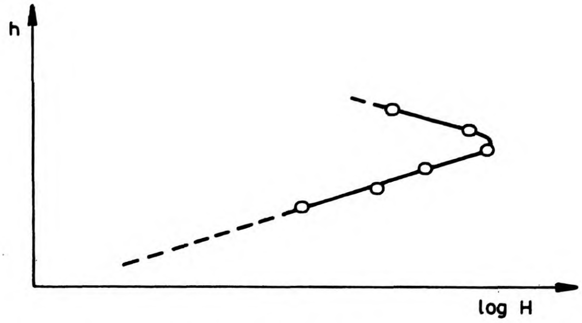

Fig. 3. In-depth distribution of the relative exposure H in the photographic layer. This dependence was determined experimentally by STRÜBIN [1]

In Figure 3, the relative exposure distribution inside the layer is shown which was published in Strübin's work [1]. The author gives no information on the actual depth at which he observed the maximum of exposition. However, from the analysis of the distribution curve illustrated in this figure it can be concluded that exposure maximum is located approximately at 1/3 of the layer thickness.

2. Model examinations

The first simulation models taking advantage of the stochastic Monte Carlo method to examine the phenomenon of light scattering in the photographic layers were carried out in the sixties [9], [10] and were recently developed by other authors [11]– [15]. Nowadays, use is made of a version of the Monte Carlo method that consists in tracing the random walk of the photons penetrating the inside of the photographic layer. The statistical examinations performed for a large number of photons penetrating the layer and interacting with the penetrated medium allow us to obtain an image of the spatial distribution of the absorption acts for photons. The absorption of a photon can be identified with the creation of the corresponding photographic effect at the same place of the light sensitive layer, *i.e.*, appearance of some suitable blackening of the developed layer. The transition of effective exposure of the light sensitive layer into the blackening distribution during the chemical development is essentially a nonlinear process which complicates significantly the nature of the problem. For these reasons only the spatial distribution of radiation absorption was subject to interpretation in the examinations carried out with the special attention paid to the changes which occur with increasing depth inside of the light sensitive layer.

The functioning of the model used in the present simulation examinations was described in [16]. Moreover, when designing the respective model the results of examinations as well as suggestions and indications given in [9], [10], [17] were taken into account. The general construction of the model has been formulated in the form of an algorithm of the computer program based on the following assumptions:

– Photons propagating perpendicularly to the layer surface hit the latter at one point.

– There are no photon reflections from the upper and lower surfaces of the light sensitive layer.

– Indicatrix of the radiation scattering by a single particle of the dispersing phase is spherical, *i.e.*, no direction of scattering is preferred.

– The distribution of probability that the photon penetrating the layer travels along the free path between the subsequent collisions with the silver halide crystals is given in the form of exponential function of which the mean free path l of the photons is a parameter.

– The probability p of photon absorption during the collision with a silver halide crystal ranges within interval from 0 to 0.01.

– The photons undergo suffer from multiple reflection while the single act of absorption ends the process of tracing the corresponding path.

– The photons absorbed already in the first collision (without scattering) create a perfectly sharp image.

– The number of photons is great enough to eliminate any fluctuations of the determined dependences.

If photons are assumed to penetrate the layer always at the origin of the accepted coordinate system and in the direction identical with the z-axis, it is possible to obtain the distribution of the effective exposure in the recorded image of an infinitesimally thin bright line on a dark background by counting the acts of absorption occurring with the increasing distance from the yz-plane. This distribution is thus the LSF $L(x)$ which characterizes the properties of a concrete light sensitive layer.

The possibilities of an exact analysis of the dependence of the effective exposure $H(z)$ on the depth in the layer (z – distance from the layer surface, *i.e.*, coordinate z)

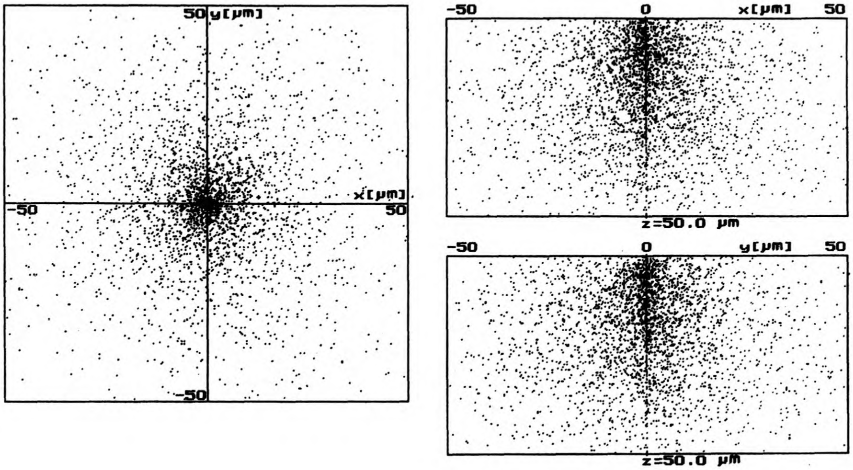

Fig. 4. Projection of the spatial distribution of the absorption acts of the photons identified with the internal distribution of the effective exposure of the layer. This distribution results from the effect of radiation scattering inside this layer. The picture on the left hand side presents a view of the layer projection on the *xy*-plane. On the right hand side the remaining projections are shown [16]

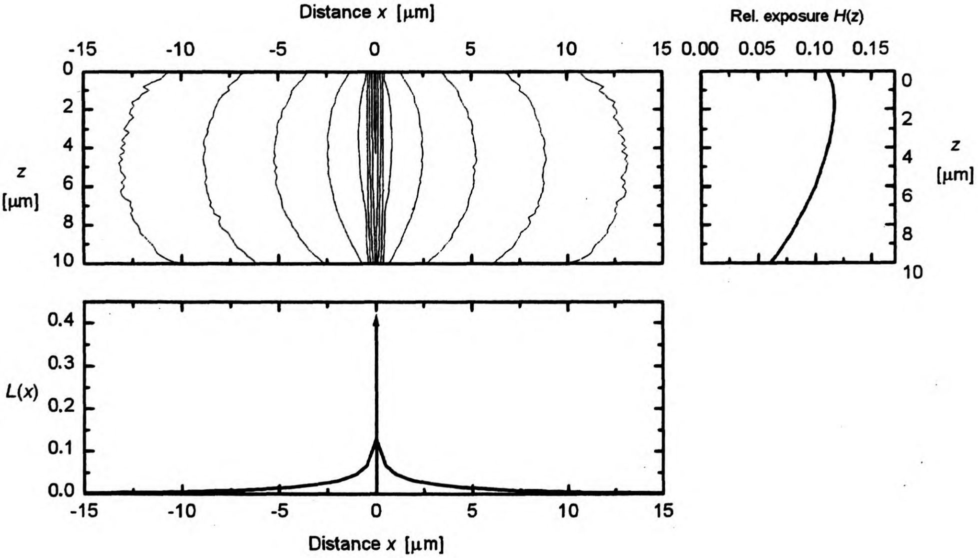

Fig. 5. Effective exposure distribution $H(x, z)$ inside the hypothetical light sensitive layer (upper picture, successive contours represent $\Delta \mathrm{Log} H = 0.3$), the corresponding LSF (lower picture) and the effective exposure distribution determined as a function of depth within the layer (right hand side picture). The curves were obtained for the h/l ratio equal to one. (Layer thickness — 10 μm, average free path — 10 μm. Results: absorption — 0.15%, reflectance — 33.9%, directed transmittance 36.8%, total transmittance — 66.0%, depth of the maximum absorption — 1.0 μm)

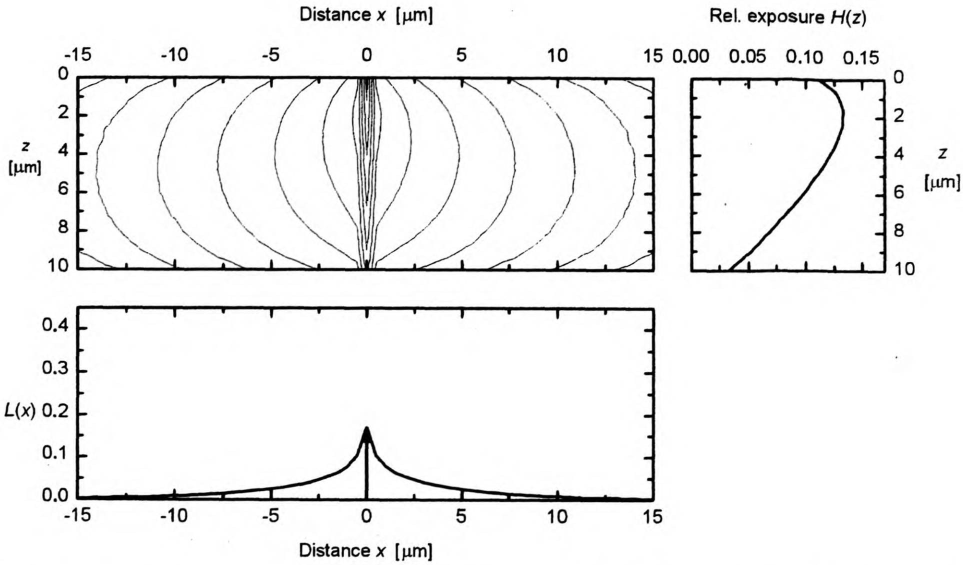

Fig. 6. Effective exposure distribution $H(x, z)$ inside the hypothetical light sensitive layer (upper picture), the corresponding LSF (lower picture) and the effective exposure distribution determined in depth of the layer (right hand side picture). The curves were obtained for the h/l ratio equal to 3 (Layer thickness — 10 μm, average free path — 3.33 μm. Results: absorption — 0.60%, reflectance — 61.6%, directed transmittance 4.97%, total transmittance — 37.65%, depth of the maximum absorption — 1.8 μm)

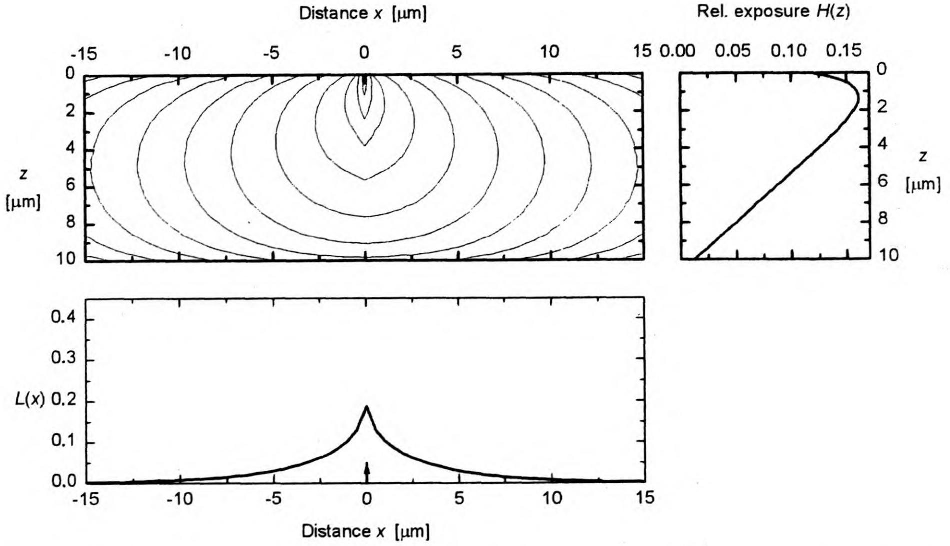

Fig. 7. Effective exposure distribution $H(x, z)$ inside the hypothetical light sensitive layer (upper picture), the corresponding LSF (lower picture) and the effective exposure distribution determined in depth of the layer (right hand side picture). The curves were obtained for the h/l ratio equal to 10. (Layer thickness — 10 μm, average free path — 1.0 μm. Results: absorption — 2.28%, reflectance — 83.7 %, directed transmittance 0.0%, total transmittance — 14.0%, depth of the maximum absorption — 1.4 μm)

and the two-dimensional distributions $H(x,z)$ seem to be especially interesting. These dependences are easy to examine by computer simulations while being very difficult to determine with the help of laboratory methods. In Figure 4, some examples of the projections of spatial distributions of the absorption acts are shown which were generated by using the elaborated computer model.

In Figures 5, 6 and 7, the generated two-dimensional distributions of exposure $H(x,z)$ are illustrated which correspond to the LSF as well as the effective exposure distribution $H(z)$ in the direction inside the light sensitive layer.

The curves presented were obtained from the simulation at a fixed $p = 0.001$ and fixed thickness of the layer h but for variable value of the mean free path l of the photon and following from above changing value of the ratio of the layer thickness to the mean free path of the photon h/l. The dependences $H(z)$ obtained in this way show maximum at certain depth under the front surface of the layer.

3. Summary

The results of the performed simulation examinations confirm the fact of appearance of a maximum of the actinic radiation absorption inside the light sensitive layers at certain distance from the surface. Additionally, it has been stated that the relative intensity and the depth at which the maximum occurs depend on both the path l of the photon and the layer thickness h. Also, the simulations have been performed allowing us to determine the dependence of the effect examined on the probability p of the absorption of the photon by the detectors of radiation.

A deeper insight into the internal distribution of the exposure in the photographic layer requires some more examinations aiming at improving the model itself. It seems also necessary to take account of the effects connected with the internal reflection of the radiation from the upper surface (and eventually from the lower one) of the substrate of the light sensitive layer. It is also worth emphasizing that the constructed model can be used not only in the research work but also in the didactic activity.

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