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Review of empirical models of photographic recording of image information

PIOTR NOWAK, BOGUMIŁ RAJKOWSKI

Institute of Physical and Theoretical Chemistry, Wrocław University of Technology, Wybrzeże Wyspiańskiego 27, 50–370 Wrocław, Poland.

In this paper, elementary problems of empirical photographic models of image information recording are discussed against the background of which a concept of our own model is presented which was used in the theoretical examinations of the influence of edge effects on acutance. The results obtained partially fill in the gap in this region of photographic structurometry and provide a starting point for further simulation model examinations and verification of the theoretical results by comparing them with the results obtained in laboratory investigations.

1. Introduction

An irreplaceable tool in theoretical examinations of the physical and chemical phenomena influencing the quality of the photographic image are computer methods of simulation examinations. The most essential effects occurring during the photographic development process are the edge effects. They appear at the border of the fields of low and high exposures (low and high density), respectively, and are characterized by some deformation of the output signal as compared to the input one. Those met most frequently are the edge effects connected with the inhibition of the development process. They are characterized by the fact that at the border of strongly and faintly exposed fields a local increase in contrast occurs which human eye interprets as an increase of the acuntance. Due to the way the edge effects are described the computer simulation models can be classified into two groups. The first one is a group of empirical models in which the chemical spread function is applied to describe the edge effects. The other group constitute the so-called diffusion models which take account of the diffusion equation as well as the kinetics equation of the chemical reactions appearing during the photographic development process [1].

2. Characteristic of the empirical models of the photographic process

A common feature of all the empirical models is the fact that the mechanism of edge effects during the chemical processing of silver halogen photographic materials is in its nature and consequences close to the effects caused by the light scattering described by the optical spread function. However, it has to be emphasized that the light scattering is connected with its diffusion in the layer during exposure while the edge effects with a diffusion of chemical molecules in the same layer occur during the photographic development. This analogy renders it possible to apply a function similar to optical spread line function $L(x)$ which has been called the chemical spread function $L_C(x)$ as referred to the edge effects.

Before presentation of the particular groups of the models a measure of intensity and consequences of the edge effects must be considered and defined [1], [2]. The simplest method of estimating the action of these effects is the method based on determination of the differences in the density of image fields remaining both within and outside the range of edge effects.

The difference in densities ΔD of the image and its background has been defined as the difference between the average values of densities D_1 and D_2 which has been determined on the strongly and faintly exposed fields, respectively, outside the range of edge effect. The measure of the intensity of the edge effects on the faintly exposed field ΔD_1 (fringe effect) is defined as the difference between the average value of the density D_1 determined in this field outside the range of the edge effect and the minimal value of density D_1' determined with the range of the edge effects. On the other hand, the measure of the intensity of the edge effects on the strongly exposed field ΔD_2 (border effect) was defined as the difference between the maximal value of the density D_2' determined within the range of the edge effects action and the average value of the density D_2 determined outside the range of the edge effects action.

The oldest model of the photographic process described in the literature and taking account of the occurrence of edge effects is the three-stage Kelly's model [3]. The scheme of the functioning of this model is presented in Fig. 1.

The input signal is the spatial distribution function to exposure $H(x)$ acting on the light-sensitive system without contribution of the scattered light. In reality, however, the light acting on the recording silver halogen layer suffers from scattering which is caused by the noncontinuous structure of this type of image information carrier. Therefore in the first stage of simulation using empirical models the input exposure distribution $H(x)$ is transformed into a real spatial exposure distribution $H_r(x)$. This stage is realized, in general, by convolution operation of the input signal function being

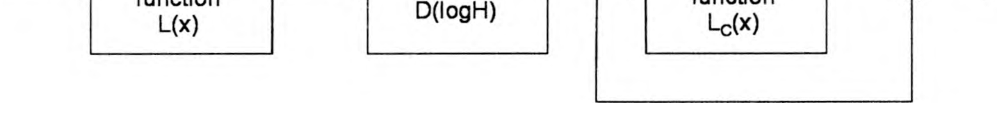

Fig. 1. Three-stage model of optical information recording in the image while applying the silver halide photographic process in which the calculation of edge effects consists in modifying the spatial density distribution.

the exposure distribution $H(x)$ with the line spread function $L(x)$. This relation is expressed by the equation

$$H_r(x) = \int_{-\infty}^{+\infty} L(x')H(x-x')\mathrm{d}x' \tag{1}$$

where $H(x-x')$ – input exposure distribution function without contribution of scattered light, $H_r(x)$ – real exposure distribution function including scattered light contribution, $L(x')$ – line spread function.

In the second stage of simulation the real exposure distribution $H_r(x)$ of the recording layer is recounted to the spatial distribution of the density $D(x)$. For this purpose the macroscope characteristic curve $D = f(\log H)$ is used which expresses the dependence of the density D on the exposure logarithm $\log H$. The density distribution does not take account of the edge effects occurring during the development. It is only in the third stage that the spatial density distribution is modified in such a way as to include the edge effects. In practice of the simulation examination this operation consists in performing the convolution of the real distribution of the density $D(x)$ with the chemical spread function $L_C(x)$. If the edge effects are connected with inhibiting the photographic development process the obtained convolution function is subtracted from the spatial density distribution obtained after infinitely long time of developer action (Eq. (2)). On the other hand, if the edge effects are connected with acceleration of the development process both the components of the real density distribution function are subjected to addition

$$D_C(x) = D(x) + SD(x) - S\int_{-\infty}^{+\infty} L_C(x')D(x-x')\mathrm{d}x' \tag{2}$$

where $D_C(x)$ – density distribution function obtained for the case of the development process in the presence of edge effects, $D(x)$ – optical distribution function obtained for the case of the development process without contribution of the edge effects, $L_C(x')$ – chemical spread function, S – constant proportional to the intensity of edge effects.

In the model described the intensity of edge effects does not depend on the absolute level of the density while being dependent on the density difference of the image and background ΔD, respectively, whereas the values of density increments ΔD_1 and ΔD_2 are equal to each other and increase proportionally to the difference ΔD of the respective optical densities of the image and the background. In spite of the fact that the Kelly's model treats the photographic development process as a linear one, it became a basis for elaboration of the other more effectively operating models of the photographic process thanks to elasticity in the range of simple modification of the calculation algorithm.

Some development of Kelly's model was proposed by SIMONDS [4], [5] in 1964 in which the nonlinear character of the photographic development process was taken into account. The scheme of the functioning of his model was the same as that of Kelly's empirical model (Fig. 1). In the Simonds model the ways of determining both the real exposure distribution $H_r(x)$ and density distribution for large surfaces $D(x)$ of the image layer are identical with the ways employed in Kelly's model. However, in the last stage of calculations in the Simonds model the spatial distribution of the density $D(x)$ is suitably modified by taking account of the edge effects. This relation is expressed by the following equation:

$$D_C(x) = D(x) + BD^2(x) - D(x)\int_{-\infty}^{+\infty} L_C(x')D(x-x')\mathrm{d}x' \tag{3}$$

where B denotes the integral of the chemical spread function defined below

$$B = \int_{-\infty}^{+\infty} L_C(x')\mathrm{d}x'. \tag{4}$$

From comparison of Eqs. (2) and (3) it follows that the factor introduced by Simonds to take account of the nonlinearity of the photographic development process is the spatial distribution function $D(x)$ which is introduced in place of constant value S. Besides, the replacement of the constant value S by the spatial density distribution function $D(x)$ renders it possible to take account of the dependence of edge effect intensity not only on the density difference ΔD in the image and the background, respectively, but also on the absolute value of the respective density of bright and dark fields D_1 and D_2. For this reason the values of density differences ΔD_1 and ΔD_2 differ from each other while the increase of magnitude as functions of ΔD is not rectilinear and is characterized by the rate of changes as compared to Kelly's model.

The Simonds model does not take full account of all the effects and relations observed in reality. First of all it ignores nonlinear dependence of the density on the surface silver concentration. This relation is expressed as follows:

$$M = PD^n \tag{5}$$

where M – surface silver concentration, P – photometric equivalent, n – exponent defining the degree of nonlinear dependence of the surface silver concentration on the density the value of which is contained within the 0.5–1.0 interval [6].

A further development of Simonds empirical model taking account of the nonlinear dependence of the density on the surface silver concentration (Eq. (5)) was proposed by NELSON [6]. This model functions according to the scheme presented earlier in Fig. 1 while the density distribution obtained after development with the participation of edge effects is expressed by Eq. (6) which was derived from Eq. (3) after having considered nonlinear dependence of the surface silver concentration on the density which finally gives the following equation:

$$D_C(x) = \left[D^n(x) + BD^{2n}(x) - D^n(x) \int_{-\infty}^{+\infty} L_C(x')D^n(x-x')\mathrm{d}x' \right]^{1/n} . \tag{6}$$

From the experimental examinations [7]–[10] it is well known that the increase of density ΔD_2 caused by the edge effects on the side of the strongly exposed field tends to some maximum after which it starts to diminish taking finally the zero value. The value of the density increment ΔD_2 tends to zero when the density in the image D_2 tends to maximal value of the density $D_{\max}$ possible to achieve for a concrete photographic material. The level of maximal value of the density $D_{\max}$ depends not only on the kind of light-sensitive material but also on the physicochemical conditions of the chemical processing [7]–[9].

Nelson's model as well as other models presented so far disregard the facts presented above. First Liekens in his work [10] and Jarvis in his work [11] presented the model taking into account the existence of the limiting, maximal value of the density increment ΔD_2 caused by the action of the edge effects. This model is a further development of Nelson's model [6] and works according to the scheme presented earlier in Fig. 1. An essential difference in operation of this new model is in relating the chemical spread function to the ratio of the density D_2 in the image to the maximal value of the density $D_{\max}$ possible to achieve by the image layer under concrete conditions of its application

$$L_{C_1}(x') = L_C(x')D_2^{m-1}\left(1 - \frac{D_2}{D_{\max}}\right)^N \tag{7}$$

where $L_{C_1}(x')$ – modified chemical spread function, $L_C(x')$ – chemical spread function applied in Nelson's model, D_2 – value of the density of the dark image field, $D_{\max}$ – maximal value of the density possible to achieve with a concrete light-sensitive material under definite conditions of development, m and N – constants characteristic of concrete light-sensitive material and definite physicochemical conditions of the photographic development process.

The exponents m and N in Eq. (7) modify the chemical spread function which influences the changes in dependence of the edge effects intensities ΔD_1 and ΔD_2 on the difference of the optical densities ΔD in the image and background. For example, in Fig. 2 the dependence of edge effects intensity ΔD_2 on the difference ΔD of the density in the image and background calculated for three values of the exponent N is illustrated. For comparison, in the same figure, also a similar dependence of edge effects intensity ΔD_2 determined as a function of ΔD but obtained from the simulation calculation based on Nelson's model ($N = 0$) is presented.

In his work [12] Jarvis presented a concept of a model which for the colour materials divides the development process into two stages. The first stage is the

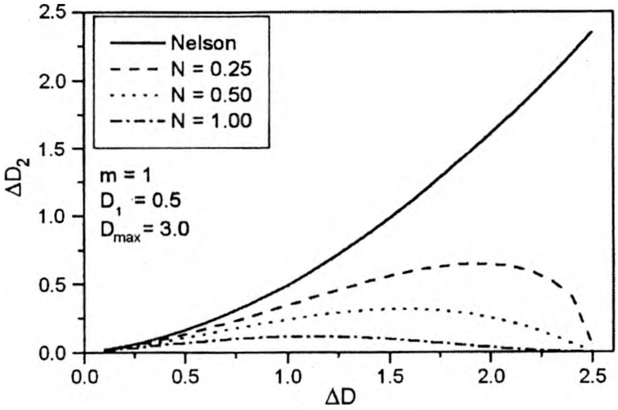

Fig. 2. Intensity of edge effects the value of which is expressed as an increment of density in the upper part of the edge function ΔD_2 as a function of the density difference in the image and its background ΔD, respectively. The calculations were carried out for three values of the parameter N. For the sake of comparison the solid line represents the results obtained from Nelson's model ($N = 0$).

development of the silver image while the other one consists in transferring the silver image into a dye image. This concept follows from the fact that during development of the colour photographic material the stage of transforming the silver image into a colour one influences to some degree the acuity of the image obtained. This model renders it possible to examine the influence of the dye component concentration and the dye cloud magnitude on the change of acutance. The scheme of the functioning of this model is presented in Fig. 3.

This model differs from the three-stage model presented earlier [11] by introducing an additional stage in which the spatial density distribution $D_{C_{\mathrm{Ag}}}$ is transformed into

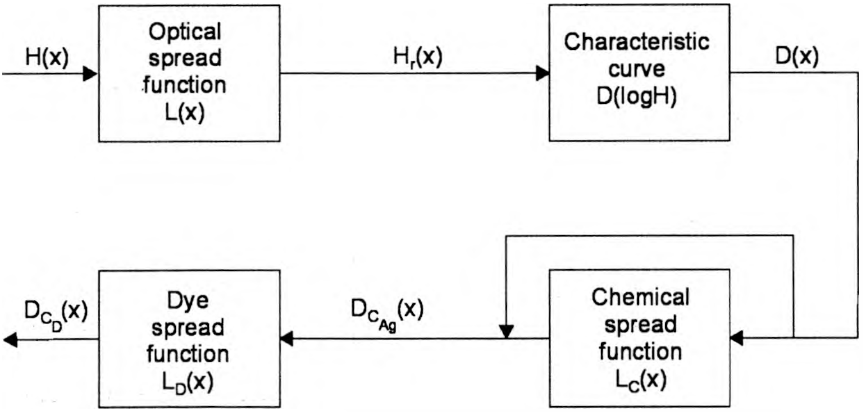

Fig. 3. Scheme illustrating a four-stage model of the optical image information recording when using the silver halide light-sensitive materials containing dye components [10]. This model takes account of the transformation of spatial density distribution $D_{C_{\mathrm{Ag}}}(x)$ in the silver halide image into a spatial density distribution of the image dye $D_{C_{\mathrm{D}}}(x)$.

a spatial density distribution of the image dye D_{C_D}. This is practically done by the operation of convolving the spatial density distribution in the silver image $D_{C_{Ag}}$ with the dye spread function L_D. The function of the spatial density distribution of the dye image is expressed by equation

$$D_{C_D}(x) = \int_{-\infty}^{+\infty} L_D(x')D_{C_{Ag}}(x-x')\mathrm{d}x' \tag{8}$$

where $D_{C_D}(x)$ – density distribution function for dye image, $D_{C_{Ag}}(x-x')$ – density distribution function for silver image, $L_D(x')$ – dye spread function.

In the eariel models of the photographic process the action of the edge effects was taken into consideration by a suitable modification of the spatial density $D(x)$ obtained from the spatial exposure distribution $H_r(x)$. Simonds in his work [13] presented a model of the photographic process in which the action of the edge effects is taken into account by modifying the spatial distribution of the exposure. The scheme of operation of this model is shown in Fig. 4.

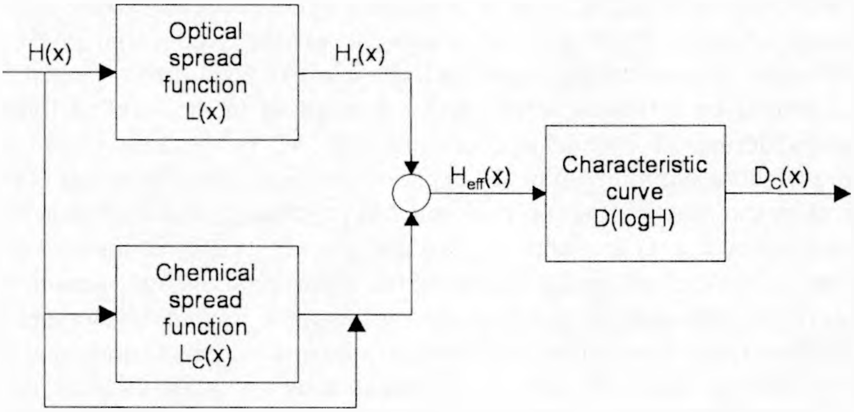

Fig. 4. Scheme illustrating the functioning of the model of the photographic recording of the image information in which the edge effect is included by modifying the spatial exposure distribution [11].

In the first stage of this model the input spatial exposure distribution $H(x)$ is transformed into a real spatial exposure distribution $H_r(x)$. This is practically realized by convolving the input (ideal) exposure $H(x)$ with the line spread function $L(x)$ identically as it was the case in the earlier models. Next, in order to take account of the edge effects the spatial exposure distribution $H(x)$ is convolved with the chemical spread function $L_C(x)$ and the values obtained are summed up with the real spatial exposure distribution which results in an effective spatial exposure distribution $H_{\mathrm{eff}}(x)$. The stage of calculation of the effective spatial exposure distribution from the input spatial exposure distribution is described by the equation

$$H_{\mathrm{eff}}(x) = \int_{-\infty}^{+\infty} L(x')H(x-x')\mathrm{d}x' + H(x)\int_{-\infty}^{+\infty} L_C(x')H(x-x')\mathrm{d}x' \tag{9}$$

where $H(x)$ – input exposure distribution operating without participation of the scattered light, $H_{\mathrm{eff}}(x)$ – effective exposure distribution function, $L(x)$ – line spread function, $L_C(x')$ – chemical spread function.

In the last stage of this model the spatial density distribution $D_C(x)$ is calculated from the effective exposure distribution $H_{\mathrm{eff}}(x)$ employing the macroscopic characteristic curve $D = f(\log H)$.

3. New concept of empirical model

The model of photographic process presented by the authors similarly as it was the case in Simonds model, in [1], [2], [14], [15] takes account of the operation of the edge effects by modifying the spatial exposure distribution. The general operational scheme of this model is shown in Fig. 5. In this model advantage is taken of the fact that the mechanism of edge effects occurring during the chemical processing of the silver halide photographic materials is similar in its character and consequences to the light scattering effect in the layer. Therefore, it is possible to use the exponential Frieser function describing the light scattering inside the light-sensitive layer [16] to describe the phenomena caused by diffusion of the active substances in the swelled light -sensitive function during its chemical processing [1], [6]. In the first stage of calculations the weighted summing up of the experimental line spread function $L(x)$ with the chemical spread function $L_C(x)$ is performed. As a result of such operation an effective spread function $L_{\mathrm{eff}}(x)$ is obtained which describes in a comprehensive way both the consequences of the light scattering during the exposure of the light-sensitive layer and action of the edge effects appearing during the photographic development process. The surface of both the optical and chemical spread functions is normalized to unity. The intensity of the edge effects is regulated by the magnitude of the contribution of the chemical spread function $L_C(x)$ to the effective spread function $L_{\mathrm{eff}}(x)$ by applying the dimensionless weighting factor ρ. This stage of the calculations is described by the equation

$$L_{\mathrm{eff}}(x) = (1-\rho)L(x) + \rho L_C(x) \tag{10}$$

where ρ is a dimensionless weighting factor describing the contribution of the chemical spread function, $L_C(x)$ to the effective spread function $L_{\mathrm{eff}}(x)$.

In this model the differentiation of the intensity of the edge effects action on the respective fields of low and high exposure is obtained by diminishing proportionally the value of the chemical spread function on the part of the low exposure field. In the consecutive stage of calculations the integration of the effective spread function is performed as well as its normalization in the limits from the value H_1 characteristic of the low level exposure to the value H_2 characteristic of the high level exposure. In this

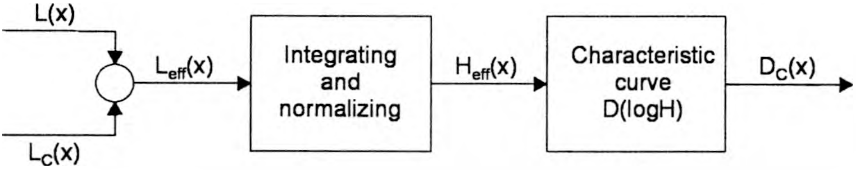

Fig. 5. Tree-stage model of optical recording of the image information when using the silver halide photographic process in which the edge effect is calculated by weighted summing up the line spread function and the chemical spread function [1], [2], [14], [15].

way a distribution of the effective exposure $H_{eff}(x)$ inside the light-sensitive layer is obtained.

Besides, this model renders it also possible to calculate the effective exposure by calculating the convolution of the input exposure distribution function $H(x)$ with the effective spread function $L_{eff}(x)$. This relation is expressed by the equation

$$H_{eff}(x) = \int_{-\infty}^{+\infty} L_{eff}(x')H(x-x')\mathrm{d}x'. \tag{11}$$

In the last stage of calculations the effective exposure distribution $H_{eff}(x)$ is recalculated into spatial density distribution $D_C(x)$ by applying the macroscopic characteristic curve $D = \log(H)$ as a result of which the edge function describing the density distribution at the border of the image and the background is obtained.

4. Summary and conclusions

An essential advantage offered by the model of the functioning of silver halide photographic process is the possibility of simple calculation of edge function for constant values of the density in image fields being outside the range of the edge effects both for the case of inhibiting and accelerating the process of photographic development. This is especially essential in the examinations of the influence of the intensity and direction of edge effects on the acutance. Since the earlier presented known empirical models did not meet this requirement the new proposed model provides an important completion of the tools used in computer simulation examinations of the edge effects and their connection acutance. Besides, the practical applicability of the proposed model seems to be greater as compared to the other models due to the use of little complicated mathematical apparatus which neither require application of advanced numerical method nor engage high calculating powers.

The prospects of broadening the calculation possibilities of the designed model are also of some importance, especially in the direction of modulation transfer function modelling which can contribute to an essential increase of the applicability of this model. It should be believed that the indicated problems can constitute an interesting trend of development of this model so far as calculations of the modulation transfer function connected only with the chemical processing of the silver halide light-sensitive materials, are concerned. These problems can be considered when taking account of the stochastically modelled modulation transfer function of the light-sensitive layers in which a hypothetical photographic image appears while excluding the phenomena occurring in the chemical processing of these layers [17].

Summing up the present considerations it should be recognized that the elaborated model of edge effects in silver halide photographic materials offers essential advantages which allow its application not only in basic examinations but also can be exploited in the expertise systems as well as in didactics in the field of photographic structurometry.

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References

[1] RAJKOWSKI B., *Investigation of edge effects, as a factors affecting the acutance in the silver halide materials for image information recording* (in Polish), TINTA, Wrocław 2001.

[2] RAJKOWSKI B., NOWAK P., Opt. Appl. **29** (1999), 275.

[3] KELLY D.H., Opt. Soc. Am. **50** (1960), 269.

[4] SIMONDS J.L., Photogr. Sci. Eng. **8** (1964), 172.

[5] *Ibidem*, p. 174.

[6] NELSON C.N., Photogr. Sci. Eng. **15** (1971), 82.

[7] AVERYANOVA M.A., FAERMAN G.P., Zh. Nauchn. Prikl. Fotogr. Kinematogr. **20** (1975), 382.

[8] *Ibidem*, **23** (1978), 166.

[9] *Ibidem*, p. 259.

[10] LIEKENS W., [In] *Image Quality Symposium*, Oxford, September 1980, Chameleon Press Ltd.

[11] JARVIS J.R., J. Photogr. Sci. **33** (1985), 212.

[12] *Ibidem*, **40** (1992), 105.

[13] SIMONDS J.L., Photogr. Sci. Eng. **9** (1965), 294.

[14] NOWAK P., Opt. Appl. **28** (1998), 95.

[15] RAJKOWSKI B., NOWAK P., Opt. Appl. **31** (2001), 185.

[16] FRIESER H., *Photographische Informationaufzeichnung*, The Focal Proces, London and New York, 1975, Chapt. 3.

[17] LATACZ L., *The modeling of modulation transfer function of heterogeneous image recording materials* (in Polish), TINTA, Wrocław 2001, p. 148.

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