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Light scattering properties of photographic emulsions. Application to grey level optical pseudocoloring*

J. A. MÉNDEZ, M. NIETO-VESPERINAS

Instituto de Optica, C.S.I.C., Serrano, 121, Madrid–6, Spain.

An optical method for grey level pseudocolor encoding in real-time, based on the scattering properties of film grain noise is proposed. The light scattered by the film is studied by means of a log-normal model applied to the wavefront emerging from the object. Three beams, each with a primary color, are used to illuminate the original black and white picture, giving a pseudocolored image.

1. Introduction

Several authors [1–6] have developed different techniques for color encoding of black and white images.

In this work, a real time optical method of grey level pseudocolor, based on the scattering properties of the photographic film, is proposed.

It is well known that a negative, which being illuminated by direct transmission gives a conventional image (Fig. 1), observed by diffuse reflection, appears as a quasi-positive (Fig. 2). If to these two images we add a third one obtained by diffuse transmission under a certain angle out of the forward direction (Fig. 3), we get three different images allowing the introduction of three primary colors and thus the direct observation of the pseudocolored image (Fig. 3a).

The diffuse reflection at the film surface has been extensively studied in the literature (see, e.g., [7]). In this paper we analyse the diffuse transmission. The scattering properties of silver halide grains of photographic emulsions have been discussed by several authors. These works are based on measurements of the power spectrum — or Wiener spectrum — of the film grain noise, manifested by random variations of the emulsion transmission, when coherent light passes through the film [8–15].

The noise power spectrum is studied by means of a log-normal model. This model is different from the checkboard [16] or the random dot model [17] used currently.

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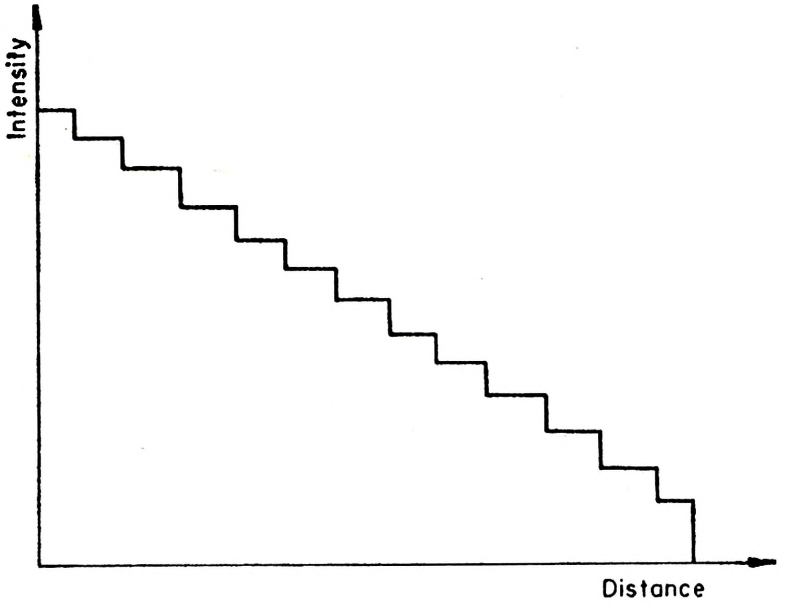


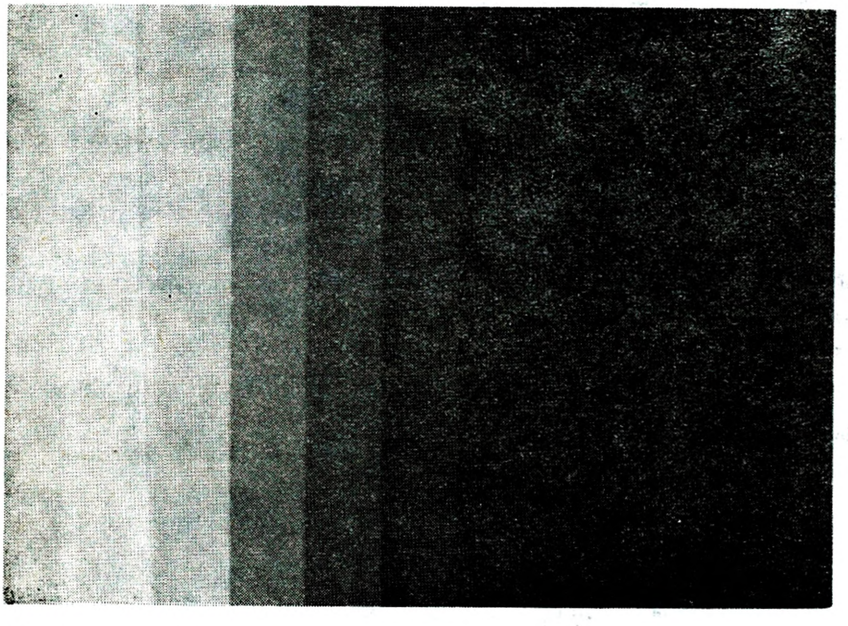
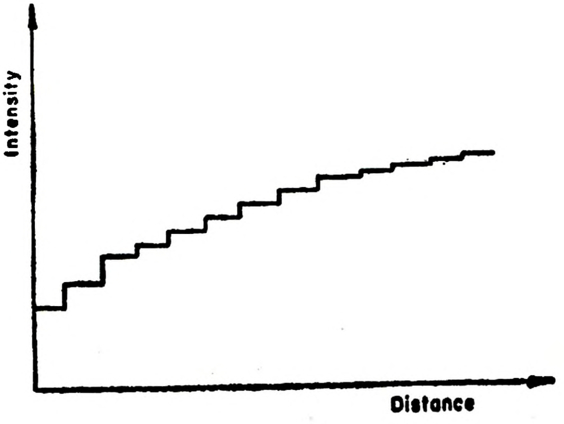


Fig. 1. Original picture



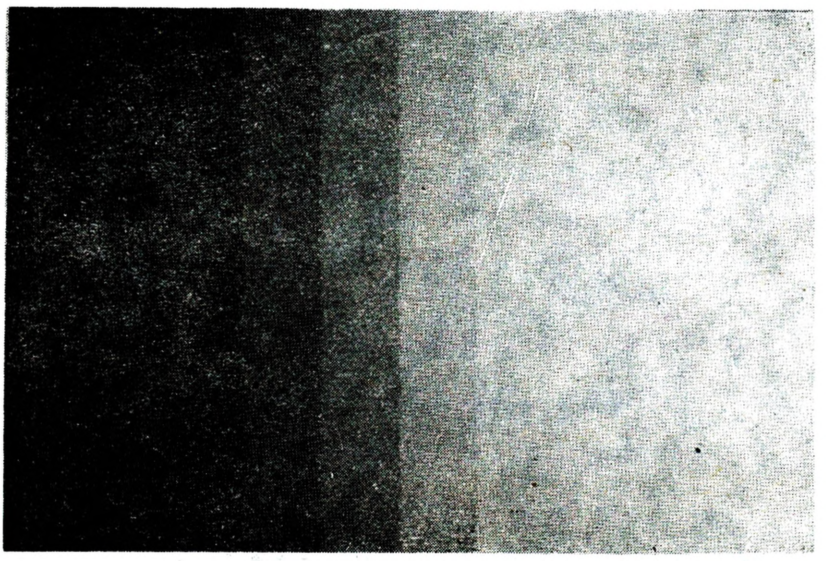
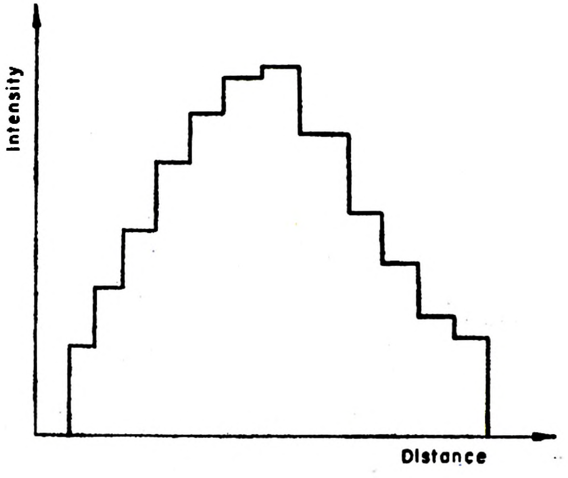


Fig. 2. Reflection image



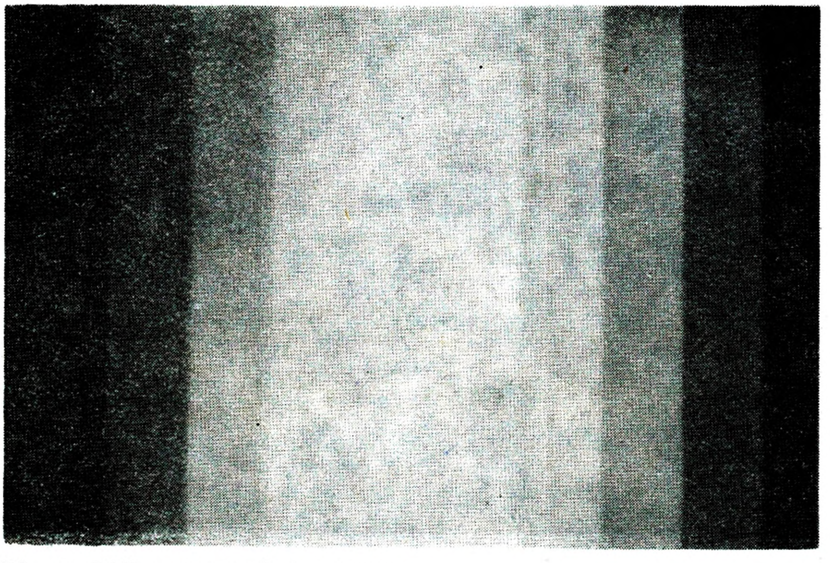


Fig. 3. Diffuse transmission image

Fig. 3a. Pseudocolored densitometric wedge

2. Theory

Let P_1 be a plane close to the photographic film and P_2 — a plane in the Fraunhofer region (Fig. 4). The scattered beam emerging from the emulsion at P_1 will be represented by

$$U(x, y) = U_0 \exp[-l(x, y)] \exp[i\varphi(x, y)] \tag{1}$$

where $l(x, y)$ and $\varphi(x, y)$ denote the random log-amplitude and phase of the wavefront, respectively, and U_0 is a constant.

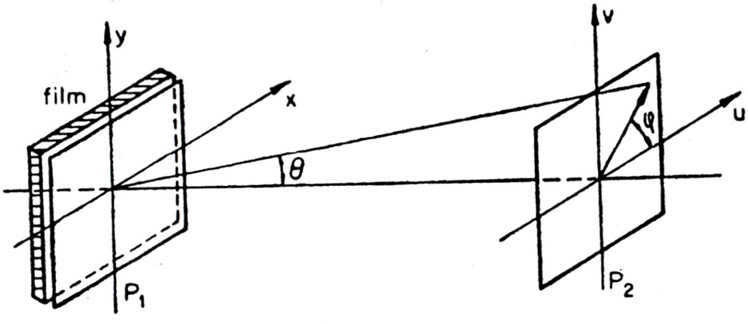


Fig. 4. Scattering geometry

The intensity at the plane P_1 is

$$I(x, y) = I_0 \exp[-2aD(x, y)] \tag{2}$$

where $D(x, y)$ is the random density and $a = 1/2 \ln 10$.

Comparing (1) and (2) we obtain

$l(x, y) = aD(x, y)$ and $U_0 = \sqrt{I_0}$.

An estimator [19] of power spectrum of the film grain noise is given by

$$\langle I(u, v)\rangle = 4\pi^2 k^2 \cos\theta \Big\langle \Big| \int\limits_{\mathscr{A}} dxdy \exp[-ik(ux+vy)] \times U_0 \exp[-aD(x, y)] \exp[i\varphi(x, y)] \Big|^2 \Big\rangle. \tag{3}$$

$\mathscr{A}$ is the illuminated area of the plane P_1 and the factor $4\pi^2 k^2 \cos\theta$ corresponds to the scalar approximation for planar random sources [20]. The angular brackets denote an ensemble average.

The joint moment generating the functions $aD(x, y)$ and $aD(x', y')$ [21] is given by

$$\begin{aligned} \Psi &= \langle \exp[-aD(x, y)] \exp[-aD(x', y')] \rangle \\ &= \exp[-2a\bar{D}] \exp\{a^2 \sigma_D^2 [1 + C_D(\tau)]\} \end{aligned} \tag{4}$$

where σ_D is the density variance and $C_D(\tau)$ is the density correlation function. For $D(x, y)$ and $\varphi(x, y)$ the Gaussian distribution is assumed [22].

The joint characteristic function of the random $\varphi(x, y)$ and $\varphi(x,' y')$ is

$$\Phi = \langle \exp[i\varphi(x, y)]\exp[-i\varphi(x', y')]\rangle = \exp\{-\sigma_\varphi^2[1-C_\varphi(\tau)\} \tag{5}$$

where σ_φ and $C_\varphi(\tau)$ are the variance and correlation function of φ, respectively.

By performing the due operations we obtain finally

$$\begin{aligned}\langle I(s)\rangle = \mathcal{I}_0 \exp[-2a(\bar{D}-a\sigma_D^2)]\exp(-a^2\sigma_D^2)\exp(-\sigma_\varphi^2)\\ \times(1-s^2)\int_0^\infty d\tau\tau J_0(ks\tau)\exp[a^2\sigma_D^2 C_D(\tau)]\exp[\sigma_\varphi^2 C_\varphi(\tau)]\end{aligned} \tag{6}$$

where $s = \sqrt{(u^2+v^2)} = \sin\theta$, J_0 is the zero-order Bessel function and $\mathcal{I}_0$ is given by

$$\mathcal{I}_0 = (2\pi)^3 k^2 \mathcal{A} U^2, \tag{7}$$

and represents the intensity that would be given in the Fraunhofer plane if there were neither absorption nor scattering in the film. The exponential factor $\exp[-2a(\bar{D}-a\sigma_D^2)]$ in Eq. (6) represents the absorption of light in the film and the quantity

$$J = \mathcal{A} U^2 \exp[-2a(\bar{D}-a\sigma_D^2)] \tag{8}$$

is the total mean intensity transmitted by the film across the plane P_1. This can be easily seen by taking the average and integrating the intensity given by Eq. (3) over the area $\mathcal{A}$. Hence, the quantity

$$\mathcal{D}_d = \bar{D}-a\sigma_D^2 \tag{9}$$

represents the diffuse density of the film [23].

The exponential factors $\exp(-\sigma_D^2)$ and $\exp(-\sigma_\varphi^2)$ represent respectively, the loss of energy from the straight-through beam by scattering in the emulsion producing the randomness of the log-amplitude and the phase of the emerging wavefront. Hence, the quantity

$$\mathcal{D}_s = [\bar{D}-a\sigma_D^2]+\frac{a\sigma_D^2}{2}+\frac{\sigma_\varphi^2}{2} = \bar{D}-\frac{a\sigma_D^2}{2}+\frac{\sigma_\varphi^2}{2} \tag{10}$$

represents the specular density [23].

Assuming that both σ_D and σ_φ are much smaller than 1, thus retaining only terms of second order in σ_D and σ_φ one obtains from (6)

$$\begin{aligned}\langle I(s)\rangle = \mathcal{I}_0 \exp[-2a(\bar{D}-a\sigma_D^2)]\exp(-a\sigma_D^2)\exp(-\sigma_\varphi^2)(1-s^2)\\ \times\left[\frac{\delta(s)}{s}+a^2\sigma_D^2 W_D(s)+\sigma_\varphi^2 W_\varphi(s)\right],\end{aligned} \tag{11}$$

$W_D(s)$ and $W_\varphi(s)$ being the spectral densities of $D(x, y)$ and $\varphi(x, y)$, respectively:

$$W_D(s) = \int_0^\infty d\tau\tau J_0(ks\tau)C_D(\tau),$$

$$W_\varphi(s) = \int_0^\infty d\tau\tau J_0(ks\tau)C_\varphi(\tau).$$

The first term in Eq. (11) represents a large central peak corresponding to the transmitted beam in the forward direction. The second and third terms represent scattering halos.

In the experiment that will be described in the next Section, σ_φ can be neglected because the random phases introduced both by the multiple scattering process inside the emulsion [24] and the variable thickness across the film are negligible.

Among the different choices of correlation functions a good fitting with the experimental data was obtained by using

$$C_D(\tau) = \exp[-|\tau|/T]$$

where T is the correlation length of the random density.

With these assumptions one obtains from Eq. (11)

$$\langle I(s)\rangle = \mathscr{I}_0 \exp\left[-2a(\bar{D}-a\sigma_D^2)-\frac{\sigma_D^2}{2}\right](1-s^2)\left[\frac{\delta(s)}{s}+\frac{a^2\sigma_D^2T^2}{(1+k^2T^2s^2)^{3/2}}\right]. \quad (12)$$

3. Experiment

Ten samples corresponding to the ten grey levels of a densitometric wedge constituted by Panatomic Film have been used.

Figures 5 and 6 show the halos obtained from Eq. (12) (lines) and the measured data (dots) for the ten grey levels. The diffuse densities for each grey level $\mathscr{D}_d$ have been computed from Eqs. (8) and (9) by measuring the total intensity $\mathscr{I}$ transmitted by the film at the plane P_1.

The values of σ_D and T obtained from the fitting of Figs. 5 and 6, the statistical mean $\bar{D}$, and specular density $\mathscr{D}_s$ obtained from Eqs. (9) and (10), respectively, ($\sigma_\varphi = 0$), and the amplitude transmittance are shown in the Table

$$T_a = \exp(-a\mathscr{D}_d). \quad (13)$$

Figure 7 shows the relative intensities scattered at 18°, 30° and 40° vs. T_a. Experimental data and theoretical values given by Eq. (12) are represented by dots and lines, respectively.

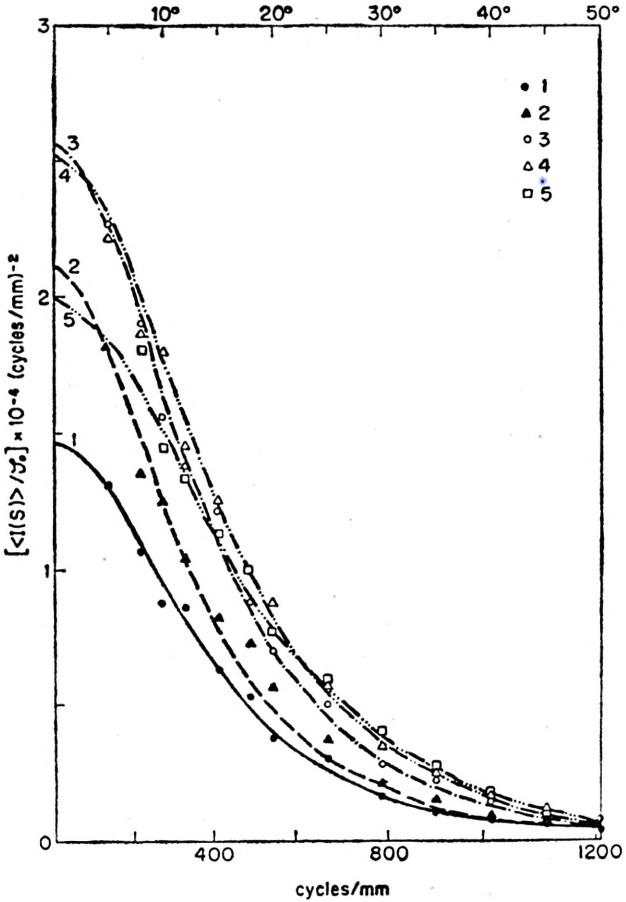


Fig. 5. Power spectra of film grain noise

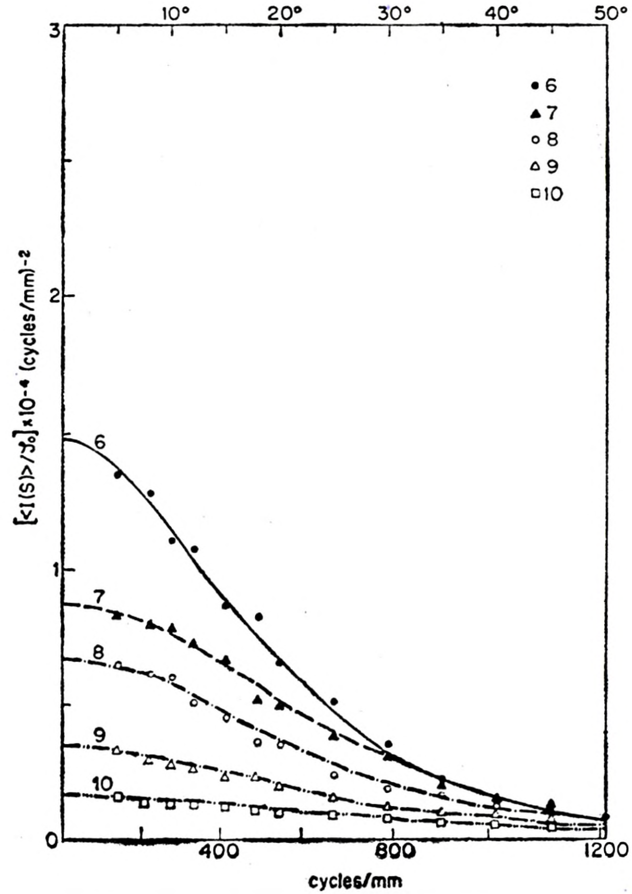


Fig. 6. Power spectra of film grain noise

These curves correspond to the diagram of the third image quoted in (Fig. 3), which is introduced in the pseudocolor method. Let us observe that the maximum intensity at 40° corresponding approximately to $T_a = 0.6$ is in agreement with our experiment and the result obtained from the random dot model.

Sample	σ_D	T (μ)	$\bar{D}$	$\mathscr{D}_s$	$\mathscr{D}_a$	T_a
1	0.035	0.318	0.051	0.088	0.05	0.95
2	0.038	0.356	0.082	0.166	0.08	0.91
3	0.051	0.318	0.143	0.265	0.14	0.85
4	0.064	0.285	0.245	0.448	0.24	0.76
5	0.076	0.247	0.377	0.676	0.37	0.64
6	0.092	0.225	0.590	0.962	0.58	0.51
7	0.131	0.159	0.830	1.284	0.81	0.39
8	0.136	0.174	1.060	1.630	1.04	0.30
9	0.146	0.159	1.324	2.036	1.30	0.22
10	0.205	0.123	1.708	2.585	1.66	0.14

This maximum is slightly shifted towards higher transmittances, as the observation angle decreases. The values of σ_D vs. $\bar{D}$, both given in the Table, are plotted in Fig. 8. The line fitted to these data follows Bayer's law [18] within the 5 % average relative error with which D is given.

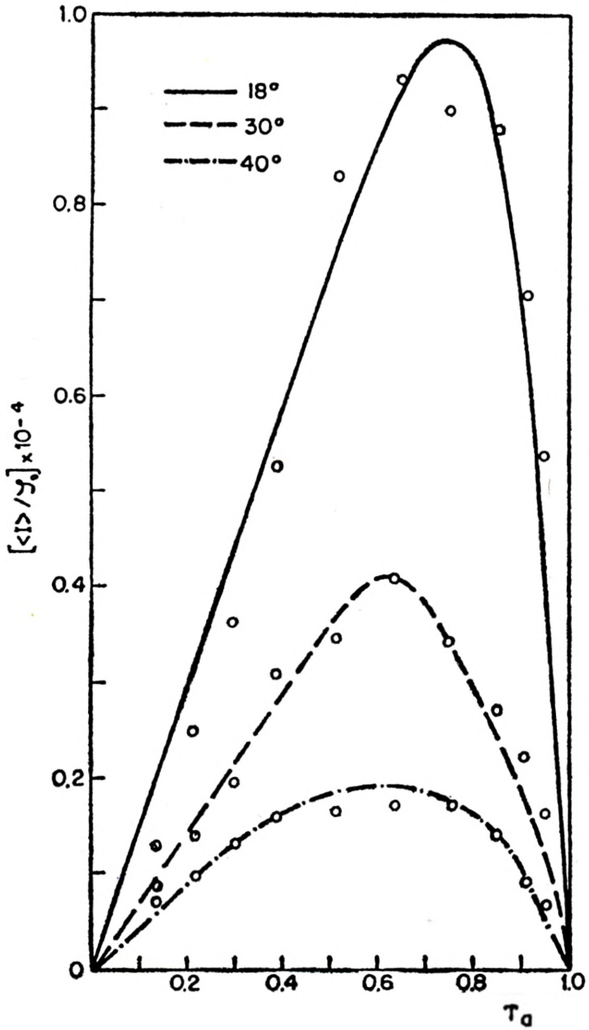
4. Optical pseudocolor method

Figure 9 shows the system for obtaining the three superimposed images of Fig. 1, each of them encoded with a primary color.

The black and white picture is illuminated with the partially coherent light beams from a Xenon arc lamp. Each color is obtained by placing in each beam an interference filter (of 630 nm, 520 nm and 480 nm, respectively). The lens L forms the image of the object in the plane P. With the red beam (1) an image is obtained after straight-through transmission in the object. Light from the blue beam (2), diffusely reflected by the photographic emulsion towards the lens L, gives a second image. Analogically, the third beam of green light (3) is diffusely transmitted by the object and gives a third image.

The three images are systematically superimposed as they come from the same object. Thus, we obtain a color encoding of the different gray levels of the original picture (Fig. 3a). According to Fig. 10 the most transparent parts of the object would be encoded in red color. Those of intermediate density would appear in a dominant green and those parts of higher density would be in a dominant blue. A continuous variation from red to green and from green to blue will take place.

Figures 11 and 12 shows two pseudocolored objects. Obviously, this code can be modified by exchanging the colors of the beams.



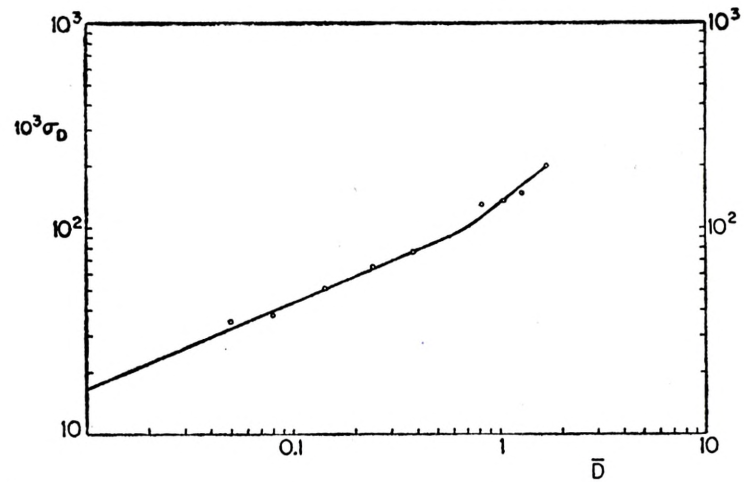


Fig. 8. Film density variance vs. the statistical mean density D

Fig. 7. Scattered intensity as a function of amplitude transmittance at 18°, 30° and 40°

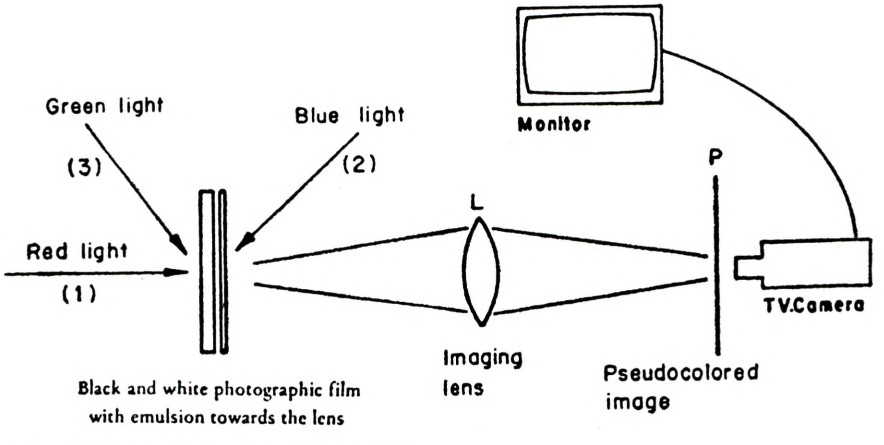


Fig. 9. Optical pseudocolor system

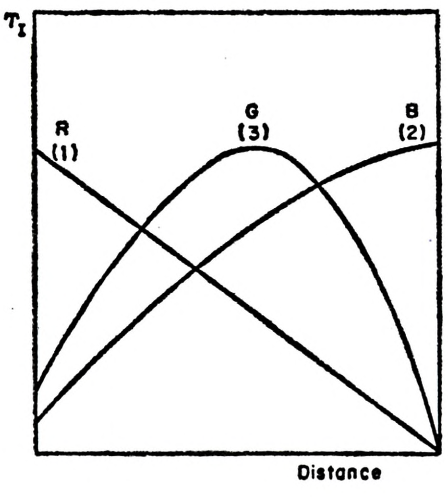


Fig. 10. Intensity diagrams of the images obtained with each color for a continuous densitometric wedge

5. Conclusions

We have put forward a simple optical method for grey level pseudocolor encoding in real-time with three primary colors, that does not need the use of coherent light.

The light scattered by the film grain noise has been studied by means of a log-normal model that applies to the wavefront emerging from the photographic film. The comparison of the theory with the experimental data shows a good agreement within the relative error of density determination.

The adjustment of the relative intensity of each beam ensures the reproduction of the encoding for a given photographic film. Under these conditions the pseudocolored image is simply obtained by placing the black and white picture with the emulsion towards the imaging lens.

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Свойства рассеяния света фотографическими эмульсиями. Применение для оптической псевдоколоризации оптической плотности

Предложен оптический метод кодирования оптической плотности псевдоцвета во времени в реальном масштабе, основан на рассеянных свойствах зернистости эмульсии. Свет, рассеиваемый эмульсией, исследуют при помощи логарифмично-нормальной модели, используемой для фронта волны, исходящего из объекта. Три пучка, каждый основного цвета, примененные для освещения черно-белого оригинального изображения, дают псевдоцветное изображение.

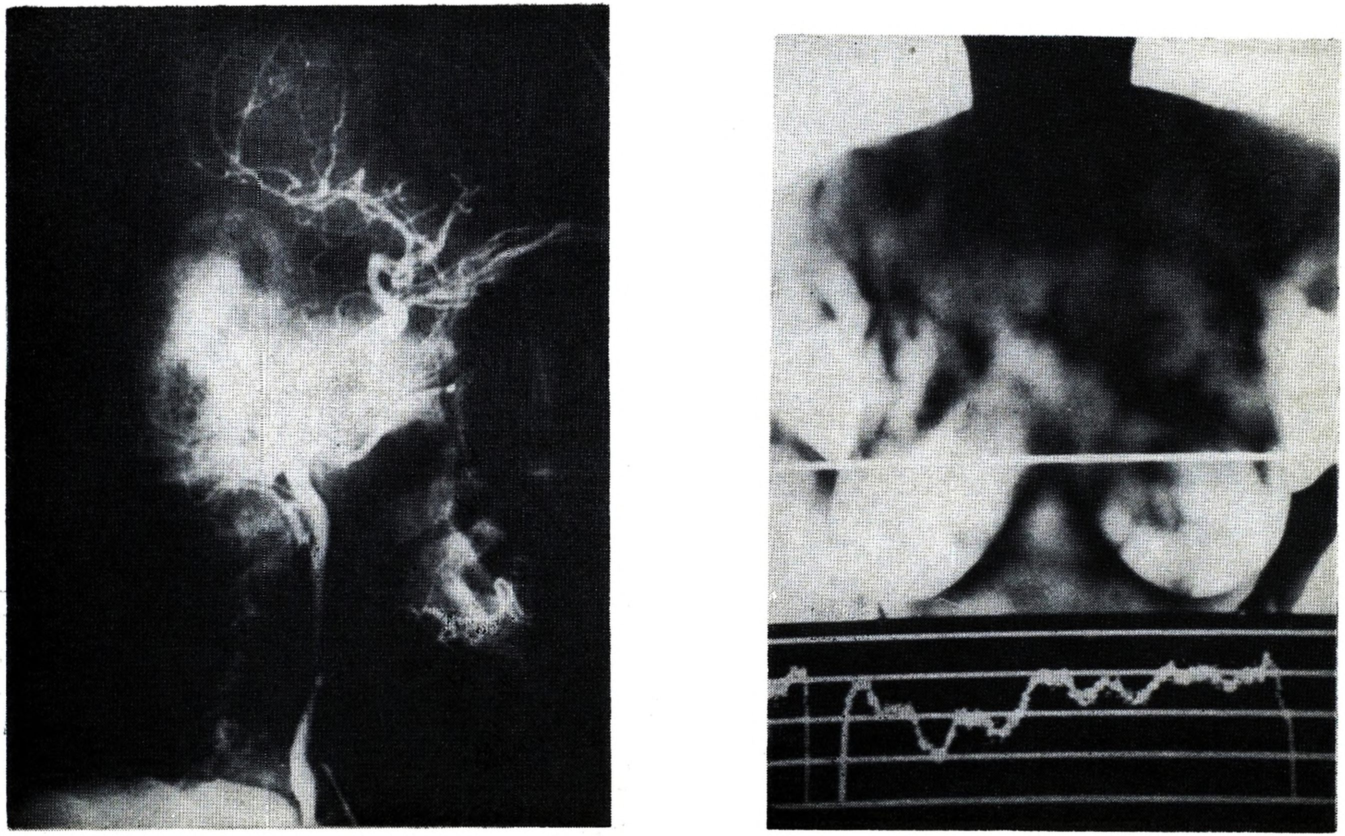

Fig. 11. Original objects

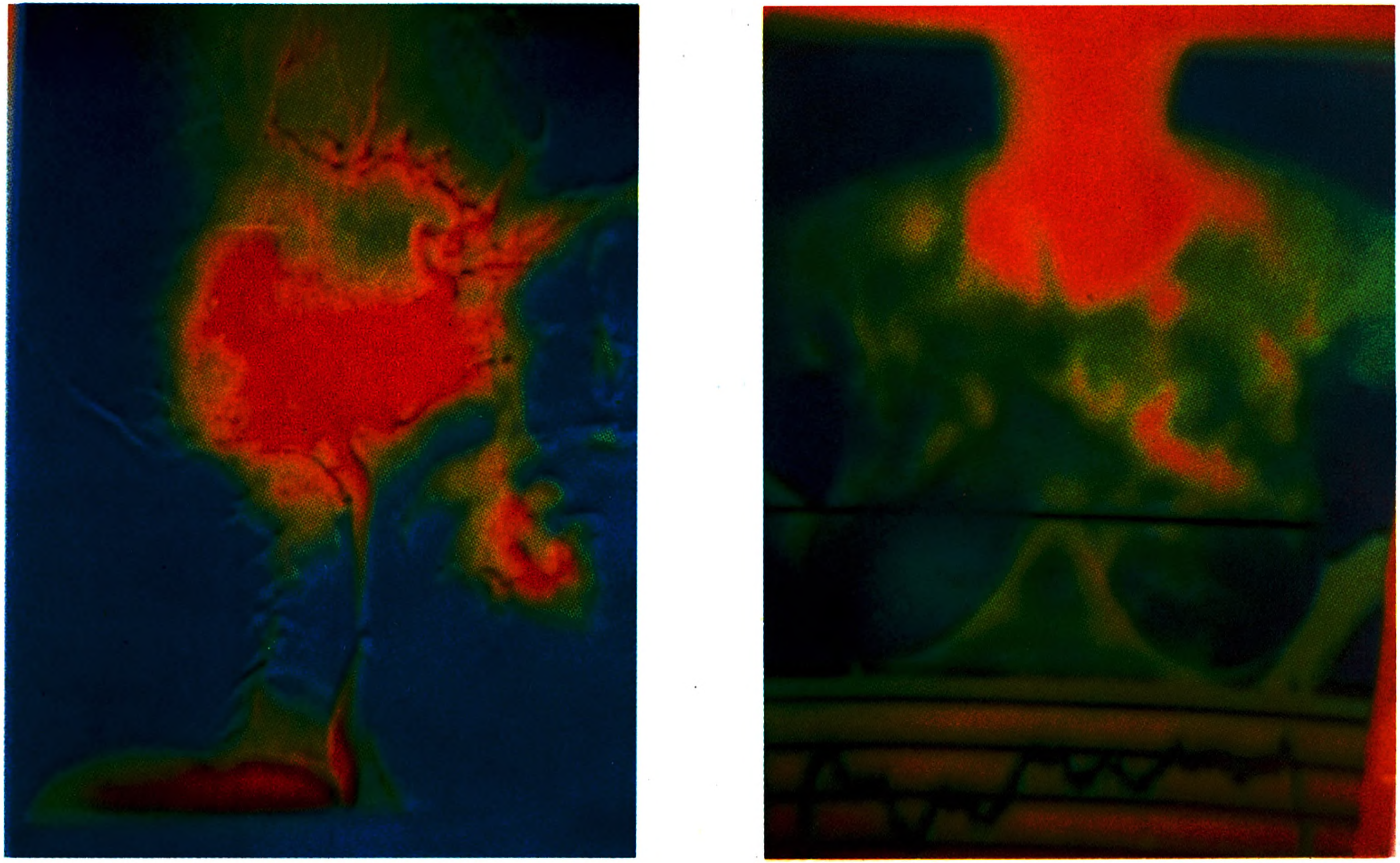

Fig. 12. Pseudocolored objects