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Film Response as a Function of Exposure

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The fact that the image-forming capability of film varies with exposure is of interest when the film is used as a detector in a photographic system. A technique for determining this capability as a function of exposure is described in this paper. Sine-wave targets of a given modulation and of several spatial frequencies are photographed with a high-resolution camera specifically constructed for this purpose. After processing, the modulation of the light transmission of the images is measured with a microphotometer. The measured transmission modulation for a given spatial frequency is modified to account for the instrumentation and is plotted as a function of exposure. These data make possible the determination of optimum exposure, the loss of image quality accompanying nonoptimum exposure, and the requirements for exposure control mechanisms. The response of the film is determined by comparison of the transmission modulation of the photographic image with the modulation of the optical image incident on the film.

This technique is shown as applied to an aerial film; therefore the image modulation values employed are relatively low to simulate the low contrast of aerial scenes. The use of information obtained by this method of evaluation improves the designer's ability to predict the performance of a photooptical system.

The light transmitted through a processed negative is of fundamental importance since it is necessarily employed in all uses of the negative. The modulation of the transmitted light, or the transmission modulation, is denoted by M_T and is defined by

$$M_T = \frac{T_{\max} - T_{\min}}{T_{\max} + T_{\min}},$$

where T is the transmittance.

With given processing conditions, the transmission modulation of an image recorded on film is primarily a function of the exposure, the modulation of the optical image to which the film is exposed, and the size of the image structure. This paper describes a method for determining the transmission modulation as a function of exposure, for given aerial image modulations and spatial frequencies.

The evaluation method proposed here is similar to that proposed by Howlett,[1] except that objective measurements have been substituted for subjective criteria. In the earlier work, resolution targets were exposed and visually evaluated. This procedure resulted in some variation due to differences in visual perception among individuals, and, more important, provided only an evaluation of the limiting resolution. The new method should permit different investigators to obtain identical results because it employs objective measurement. It also accounts for the object contrast variations that Kardas[2] observed, except that modulation, rather than contrast, was chosen to evaluate this effect. Finally, data obtained indicate that variations due to spatial frequency can be handled by this evaluation method, satisfying the requirement, which MacDonald[3] has discussed, to "tune" the photooptical system to match detail size. Even more important is the fact that this instrumental evaluation describes the image at all spatial frequencies and not merely the spatial frequency at the visual limit of resolution.

Procedure

A sample of the film being evaluated is exposed in an instrument called a microcamera (Fig. 1). In the

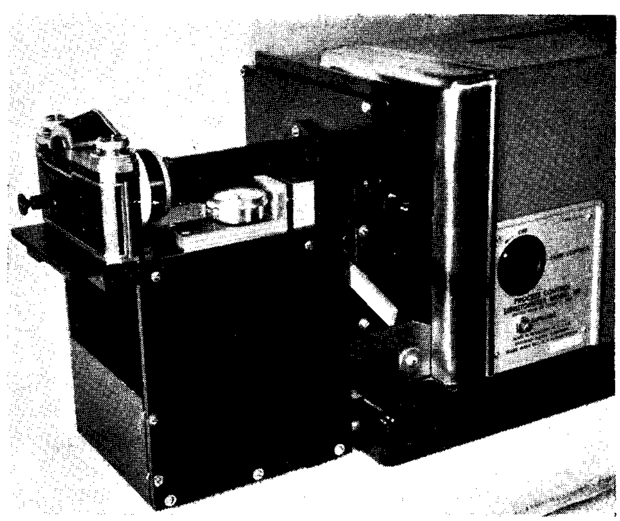

Fig. 1. Microcamera.

Presented at the Annual Conference, Binghamton, N.Y., 25 May 1961. Received 4 May 1961; revised 26 June 1961.

1. L. E. Howlett, *Can. J. Research*, **24:** 1 (1946); *ibid.*, **26:** 60 (1948).
2. R. S. Kardas, *Phot. Eng.*, **5:** 91 (1954).
3. D. E. MacDonald, *J. Opt. Soc. Am.*, **43:** 290 (1953).

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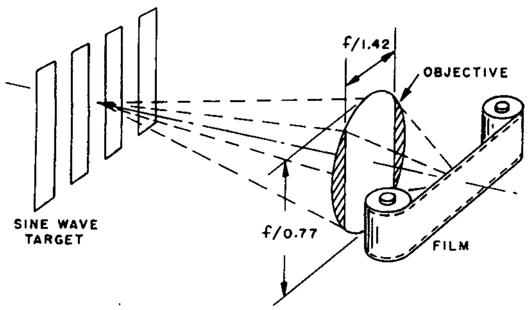

Fig. 2. Schematic of optical arrangement of microcamera.

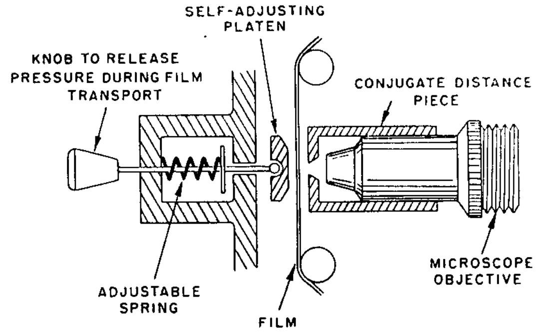

Fig. 3. Microcamera film platen mechanism.

microcamera, the film is exposed to the image of a sine-wave target at a reduction of approximately 25 ×. A sensitometer is used as a controlled light source.

The exposure time and spectral composition of the light source can be varied and should be identical to conditions of the photooptical system for which the film is being evaluated. Calibrated neutral density filters are used with the microcamera to vary the light intensity in increments of 0.1 log meter-candle-seconds.

Targets for the microcamera were photographically made on Kodak High Resolution Plates and processed to yield spectrally nonselective and practically grainless images. Each target consists of long lines and spaces of one frequency, the transmission of which varies sinusoidally. The effective modulation of the target image is varied by exposing the film sample twice: first to an open field and then to the target. Tests show that this procedure is equivalent to one exposure if the second exposure is made within a few minutes of the first, and if the time between exposure and processing exceeds 1 hr. Thus any sine-wave target of a given modulation can effectively expose on the film sample an image of any modulation lower than that of the target.

An apochromatic microscope objective, designed for use without a microscope slide cover glass, images the target onto the film. The objective is of 8-mm focal length and the aperture is essentially rectangular (Fig. 2). The original aperture was circular, $f/0.77$. Since the film was evaluated for use in an $f/1.42$ photooptical system, to simulate the angle of incidence of light on the film, the short dimension of the aperture was set equivalent to $f/1.42$ and is perpendicular to the lines of the target.[4] The long dimension of the aperture, being parallel to the lines of the target, does not affect the focus or resolution of the lines, and is thus made as large as possible, equivalent to $f/0.77$, in order to transmit as much light as possible.

The emulsion of the film sample is held in the focal plane of the microcamera, repeatable to within 0.5 μ, by a film platen mechanism (Fig. 3). Because the film is pressed onto the conjugate distance piece, which is mounted onto the objective cell, variations of base thickness do not affect the focus position of the emulsion. The pressure the platen exerts is adjustable and is such that it is sufficient to hold the film against the distance piece[5] but is not excessive, which would cause the emulsion to bulge into the 1-mm-diameter aperture of the distance piece. Care is exercised to maintain the film transport mechanism free from dust particles and to operate the camera in a reasonably constant temperature environment to attain correct placement of the emulsion in the focal plane.

All exposures in a single test are made on a small area of the film to avoid variations of results which might otherwise arise due to processing variations. The exposed film is accompanied during processing by a sensitometrically exposed film sample.

After processing, the resulting images are scanned with a microphotometer. A slit is imaged onto the traveling film with a microscope objective and aperture identical with the objective of the microcamera. The slit image is 2.5 μ wide and 125 μ long, which is one-eighth the length of the film image. The output of the microphotometer is graphically recorded and represents the photomultiplier output voltage which in turn represents transmission of the image. The modulation (M_A) of brightness (B_A) of the aerial image incident on the film in the microcamera is equal to the modulation of the target (M_0) as modified by the objective lens L_1 (Fig. 4). As mentioned previously, lens L_1 contains a rectangular aperture, the transfer function for which is:

$$\tau_{L_1} = 1 - N\lambda\nu \text{ for } \nu \leqslant 1/N\lambda$$

where N = f-number of objective
λ = peak wavelength of light in millimeters
ν = frequency in cycles per millimeter

Similarly, the image of the microphotometer slit is modified by lens L_2, which is identical to lens L_1. Account is made also for the finite width of the slit by its transfer function:

$$\tau_S = \frac{\sin \pi\delta w}{\pi\delta w}$$

4. J. M. Gregory, *Proc. Phys. Soc. (London)*, **6**: 769 (1958).

5. G. W. W. Stevens, *Microphotography*, John Wiley and Son, Inc., New York, 1957, pp. 116–127.

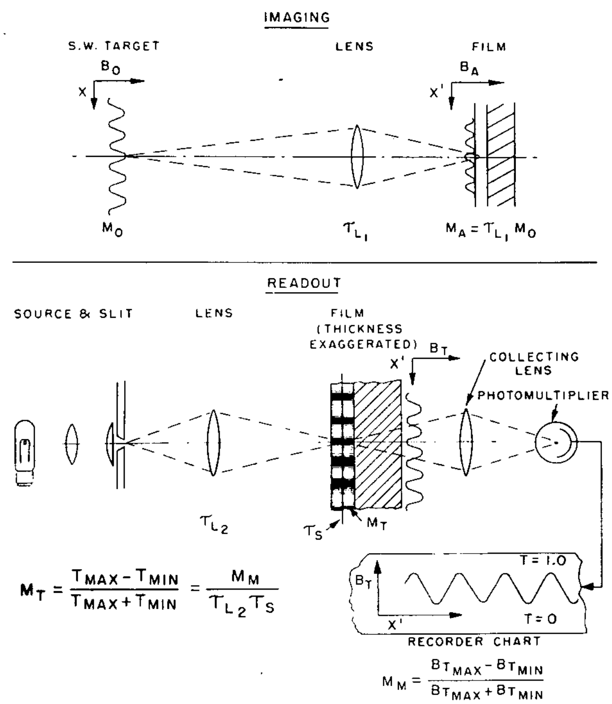

Fig. 4. Schematics of instrumentation and functional relations.

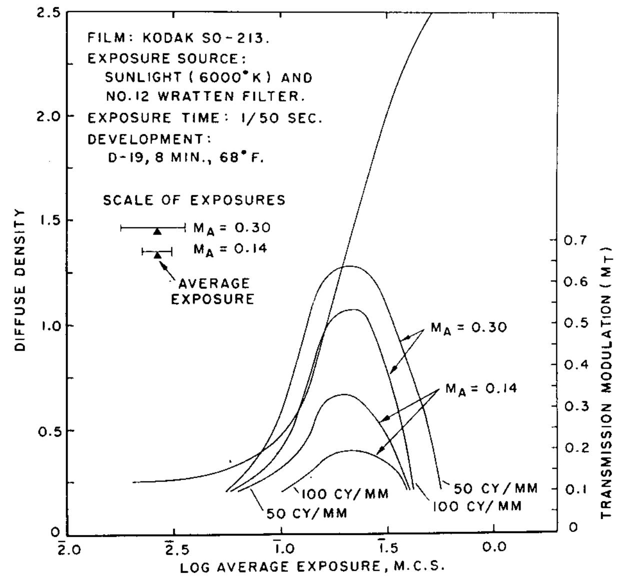

Fig. 5. Transmission modulation and diffuse density as a function of log average exposure for Kodak SO-213 Film. Transmission modulation is parametric in spatial frequency and modulation of image (M_A) incident on the emulsion.

where δ = width of slit image in millimeters
w = frequency of target image on film in cycles per millimeter

The average measured transmission modulation (M_M) of ten cycles on the microphotometer recorder chart is determined, ten cycles being chosen to reduce fluctuations due to granularity. The measured modulation (M_M) represents the transmission modulation (M_T) of the film image as modified by the finite width of the slit image and the slit imaging lens L_2:

$$M_T = \frac{M_M}{\tau_{L_2} \tau_S}$$

Since the photorecording process is generally nonlinear, the spatial variation of transmitted light is sinusoidal in only a small range of exposures, and this correction for readout instrumentation is merely a first order correction which ignores the effect of harmonic distortion caused by any nonlinearity. This procedure is followed for several exposures, for each spatial frequency of the target images, and for each modulation of interest.

It should be noted that residual primary experimental errors will yield values of M_T lower than actual M_T values. Such experimental errors include:

1. Nonoptimum focus of the microcamera image
2. Nonoptimum focus of the microphotometer objectives
3. Misalignment of parallelism of slit and image lines
4. Modulation reduction caused by the thickness of the emulsion which may significantly exceed the depth of focus of the slit image[6]

The transmission modulation (M_T) for a given spatial frequency is then plotted as a function of log average exposure (Fig. 5). These curves are parametric in modulation of the aerial image incident on the film (M_A), and the values chosen should be matched to those modulations anticipated; in this case, low modulations were chosen to simulate scenes photographed by airborne cameras. The characteristic curve is also plotted on the same abscissa, so correlation can be made between transmission modulation and density.

Applications

The determination of transmission modulation as a function of exposure, spatial frequency, and modulation of the aerial image incident on the film allows the photooptical system designer to optimize system performance by judicious manipulation of these parameters. (It must be recognized that since the transmission modulation is determined from peak transmission values without regard to wave form, two equal values of M_T may not necessarily represent images with completely similar visual interpretability.) For instance, two different transmission modulation results might be obtainable, as shown in Fig. 6, and the choice of the best system in this case depends on the exposure range anticipated. A photooptical system and film–processing combination producing Curve B probably is better for the narrow exposure

6. N. K. Southwold and W. G. Watters, *J. Phot. Sci.*, 7: 174 (1959).

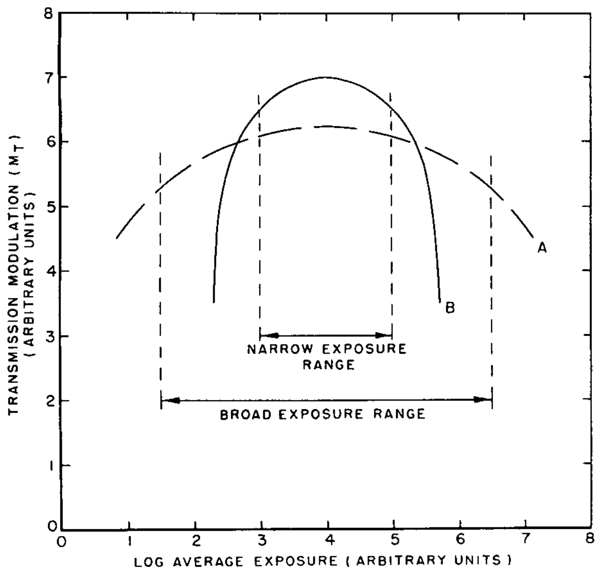

Fig. 6. Hypothetical results and exposure ranges for applications discussed in text.

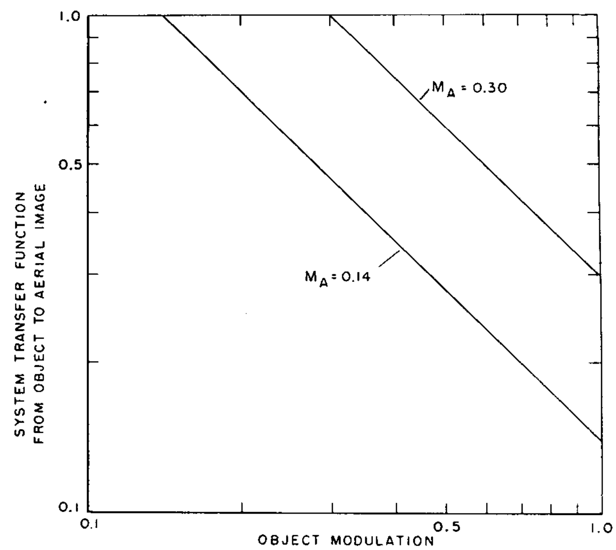

Fig. 7. Combinations of system transfer function and object modulation which will produce aerial image modulations (M_A) equal to those of Fig. 5.

range, but the combination producing Curve A probably is better for the broad exposure range.

The combination producing Curve A might also be better if a small object brightness range with considerable uncertainty in minimum object brightness is anticipated; usually this is the case in aerial photography. Conversely, if transmission modulation of 0.65 is required, then the combination producing Curve B should be employed, and precise exposure control should be added to the photooptical system.

Curves of the nature of those in Figs. 5 and 6 can also be used to set a tolerance on exposure time and/or object illumination, provided the minimum acceptable transmission modulation is known. In the case of aerial photography, the tolerance on object illumination can be used to derive an operational envelope for type of terrain (object modulations), weather (haze), and solar or lunar altitude (season, latitude, and local time). With any system in which image motion is a problem, performance can be accurately evaluated to determine whether less motion obtained by reducing exposure time is advantageous.

The fact that one curve applies to only one spatial frequency and aerial image modulation is not as restrictive as it might first appear. Figure 7 illustrates the range of system transfer functions and object modulations to which the results illustrated in Fig. 5 can be applied directly.

A new property of the photographic recording process is defined as its gain, G, where:

$$G \equiv M_T/M_A$$

Graphical plots of G as a function of M_A (and parametric in spatial frequency) are found usually to be smoother than plots of M_T as a function of M_A for low values of M_A, and this permits more accurate interpolation between transmission modulation curves, as needed, to provide information for design estimates. It should be noted that, for the sample of Fig. 5, the gain is greater than unity at the peak of the transmission modulation curve; specifically, there is a modulation increase.

Conclusions

In conformity with other recent studies, this evaluation method is basically a form of sine-wave modulation analysis, and is thus compatible with the powerful analytic tools developed in those studies. However, this evaluation applies to the modulation of light transmitted through a processed negative and does not yet fully account for harmonic distortion resulting from any nonlinearity in the photorecording process. Nevertheless, the transmission modulation of the processed negative seems to be fundamental, since it is necessarily employed in all uses of the negative. Transmission modulation should be distinguished from the sine-wave response of a film as customarily reported by film manufacturers.[7] Furthermore, this method of evaluation shows transmission modulation as a function of exposure, modulation of the aerial image causing the exposure, and spatial frequency. The added complexity of several curves provides the photographic system designer with more precise information.

Acknowledgment

The authors gratefully acknowledge the assistance of many colleagues and especially numerous discussions with R. V. Shack.

7. R. L. Lamberts, *J. Opt. Soc. Am.*, **49:** 425 (1959).