PHOTOGRAPHIC IMAGE QUALITY: PREDICTION AND ANALYSIS

Milton D. Rosenau, Jr.
The Perkin-Elmer Corporation
Norwalk, Connecticut, U. S. A.

Presented at

Symposium of Commission I
International Society of Photogrammetry
London, 19-23 September 1966

PHOTOGRAPHIC IMAGE QUALITY: PREDICTION AND ANALYSIS

Milton D. Rosenau, Jr.
The Perkin-Elmer Corporation
Norwalk, Connecticut, U.S.A.

ABSTRACT

Optical transfer functions have been applied to both the prediction and the analysis of image quality in photo-optical systems with considerable success, but there are limitations. The optical image quality depends on the wavefront shape, the object's apparent modulation, and image motion, for which optical transfer functions can easily be applied. However, the film effect on the optical image is non-linear and requires treatment by other techniques. Since aerial photography is obtained in broad wavelength regions, there is a further requirement to consider chromatic effects, and for this, polychromatic optical transfer functions are now being applied. The prediction of photographic image quality requires assumptions and a probabilistic treatment is needed. The analysis of photographic image quality for diagnosis of camera performance requires a comparison of the actual image with the expected image. Examples will illustrate these points.

I. INTRODUCTION

There are basically two different problems in considering photographic image quality. The first problem is prediction, that is, estimating how well a photo-optical system will perform. The second problem is analysis, that is, deciding how well it did perform.

In predicting photographic image quality, the concern is to select among candidate photo-optical systems, to permit intelligent design tradeoff, or to create specifications for subsequent acceptance testing. In the process of making predictions, it is necessary to deal with unknowns which require some assumptions, and it is generally desirable to recognize that the variability of some aspects is best handled by a probabilistic treatment.

Analysis of photographic image quality is important for the conduct of acceptance tests and to provide diagnostic clues so that residual defects may be located. Analysis for acceptance testing is quite straightforward, being essentially a "go-no go" process. Analyzing photographic images to provide a clue to system imperfections is a difficult task but it can be successfully accomplished if the analyst has a thorough understanding of the photo-optical system so that he knows the orientation and plausible magnitude of image quality losses attributable to each subsystem.

II. THE PHOTOGRAPHIC PROCESS:

In aerial photography a linear treatment can be applied between the ground object and the aerial (or exposure) image, but a non-linear treatment is required between the aerial image and the photographic image.[1,2]

The linear portion of the photographic process is concerned with the modulation (or contrast) of the object and its subsequent alteration by non-image forming light received at the focal plane. The linear portion also involves the optical transfer function of the imaging process, and here we are concerned with a multiplication of two transfer functions, one due to the optical wavefront and a second due to an image motion.

Optical wavefronts are rather like a mermaid. Everyone presumably knows what they are but we have not actually got one that we can exhibit. For our purposes now, the important characteristics are depicted in Figure 1. In Figure 1A, a point on the ground is shown emitting a spherical wavefront. This passes through a homogeneous atmosphere and arrives at a perfect lens where it is reshaped to a spherical wavefront convergent on the Gaussian image point. This produces an intensity distribution with Airy rings as illustrated at the top of the figure. In Figure 1B, the intervening atmospheric turbulence is shown to distort the perfectly spherical wavefront which then is still somewhat deformed after transmission through the lens, and this produces a somewhat unsharp image. In Figure 1C, we illustrate a highly artificial atmospheric distortion putting a notch in the wavefront. In Figure 1D the atmosphere is perfect but the lens somewhat imperfect and the wavefront which results is still imperfect. In Figure 1E there is illustrated an imperfect wavefront and imperfect lens with imperfections exactly compensating each other, and this would produce a perfect wavefront imaging to a diffraction pattern. This latter situation is highly improbable, of course, but does illustrate the point that it does not matter where a wavefront becomes distorted, but it is only the shape of the wavefront in the exit pupil of the lens which determines the intensity distribution in the image.

In Figure 2 the means by which an optical transfer function is computed is shown.[3] While the equations look imposing, it is a straightforward computation and simply means that the shape of the wavefront in the exit pupil contains all of the information about the optical behavior of the lens.[4]

Image motion has been extensively treated elsewhere.[5,6] The points to bear in mind now are that this transfer function is independent of the wavefront transfer function and that it depends only on the relative motion of the image and the film.

The linear relation is illustrated in Figure 3. An object is imaged through the atmosphere, through the boundary layer (which is a locally disturbed atmosphere near the photographic airplane), through the window in the photographic airplane, through the camera lens, where there may be some imperfections in focus and image motion, to produce an aerial image which impinges on the film while the shutter is open. The three independent factors which influence this imaging process are the reduction of the object's inherent modulation (M_o) by scattered and added non-image forming light,[1,7] ϕ, and the two transfer functions which we have just discussed, the product of which is $T(k)$.

The film is non-linear so a sinusoidal intensity distribution is not transmitted as a sinusoid.[8] In addition, film is grainy and effectively adds noise to an otherwise generally smooth intensity distribution.[2,9-11] The most satisfactory way to treat this difficulty depends on the consideration at hand. In predicting resolution, for instance, modulation detectability curves have proven quite satisfactory.[12,13] Other treatments are possible, but, essentially, the prediction of the transmittance of the film depends on knowing the aerial image intensity distribution impinging on the film, and secondly the exposure of this with respect to the characteristic curve. With this information it is possible to predict the mean transmittance of the film, and then noise may be added to this statistically.

III. POLYCHROMATIC OPTICAL TRANSFER FUNCTIONS:

Lenses are generally designed to give a good image in a single monochromatic line, typically the sodium (n_D) line in the middle of the photographic region. Then, as illustrated in Figure 4, the design is changed to provide good color correction at two other wavelengths, typically the mercury (n_e) and hydrogen (n_C) lines. The designer will very often examine the modulation transfer functions at each of these wavelengths, and, in effect, the phase transfer function by examination of the lateral color. But, in aerial photography, lenses work over a continuous spectral region with a relative intensity that is determined by the scene illumination, the spectral reflectance of the scene, the spectral transmittance of the lens-filter combination, and the spectral sensitivity of the film. Because of this it is desirable to compute an optical transfer function which is descriptive of the behavior of the optical system in this entire spectral region.

To provide an example, we will report on a study of J. G. Baker's Geocon lens,[14] Figure 5. As shown in Figure 6 the modulation transfer function varies considerably with wavelength. This lens is a severe example of chromatic dependence because it has so many glass types to achieve a very wide field, flat focal plane, large relative aperture and low distortion.

As shown in Figure 7, we use four steps in computing polychromatic transfer functions. (An alternative technique has also been discussed.[15]) The first three are the same steps which are necessary to compute the monochromatic transfer functions while the last step provides an approximate polychromatic transfer function. To investigate the approximation, we apply Simpson's Rule at 3, 5, 7, 9, 11 and 13 wavelengths distributed in the operational spectrum, as shown in Figure 8. For this lens, the on-axis results are shown in Figure 9, and some off-axis results in Figure 10. In this particular instance, the polychromatic transfer functions computed with nine wavelengths would be satisfactory for most purposes.

Another problem which arises in testing of lenses is that the laboratory tests are sometimes carried out using spectral regions which are different than the operational spectrum. For instance, as shown in Figure 11, using a tungsten source and a photoelectric detector produces a relatively blue spectrum as opposed to the operational spectrum for which the previous computations were made. In such a laboratory situation the polychromatic transfer function of the lens may be quite different than the operational case as shown in Figure 12.

IV. PREDICTION:

In making a prediction of camera performance, the analytical technique must be carried out in some straightforward method. The use of polychromatic transfer functions (Section III) within the framework of the model of the photographic process (Section II) is a rational way to make these predictions. However, there are two very important considerations which must be properly understood. The first is that assumptions have to be made. Second, performance prediction must be done probabilistically because of inherent variability in the aerial photographic process, and, for this large computers appear to be necessary.

In predicting performance to select among candidate systems or make design choices, assumptions must be made principally about the magnitude of residual image motion, and the magnitude of focus imperfections. For instance, in a camera just being designed, the actual performance of final mechanisms is unknown and must be estimated based on assumed design success.

The basis for probabilistic treatment has been described previously.[16] In recent years, we have done considerable work to further evolve the prediction technique, but it still requires critical testing before a new report is justified. What is worth remembering is that the atmosphere, the magnitude and direction of image motion and the optical transfer function are all variables from one photograph to the next and in some cases from place within a photograph. The variable behavior of film can be important.

Figure 13 distinguishes the differing requirements among the three main prediction purposes. Since acceptance tests may be carried out under known conditions, assumptions may not be needed, but the real variance of the measurement technique is crucial.[17]

V. ANALYSIS

When photographic images are measured for resolution, there will be a variation as illustrated in Figure 14. If the analysis is for the purpose of acceptance testing, standard statistical techniques can be applied to decide if the system is acceptable with respect to the predicted resolution spread.

In the case of camera fault diagnosis in flight testing, the situation is more involved because there is generally a larger variation in resolution and even more of this variation is not due to the camera. This is summarized in Figure 15 for both edge gradient analysis[18,19] and resolution targets. Statistical treatment by Student's t-test can be applied to determine if the actual performance is significantly different from prediction. If the difference is significant, the cause may be deduced by the clues catalogued in Figure 16, but it is also important to verify that the magnitude is plausible. It is not apparent that most diagnostic analysis is done this carefully today, so we have the prospect of further advances in this area.

ACKNOWLEDGEMENTS

The method of computing polychromatic optical transfer functions was proposed by A. Offner and D. V. Lundholm, the implementation was carried out by D. V. Lundholm with programming assistance from D. Milson and R. A. Rissolo, and J. Hoogland offered valuable guidance in the required refractive index interpolation. It is a pleasure to acknowledge these contributions and those from other colleagues.

REFERENCES

[1] Rosenau, M. D., Phot. Sci. and Engr. 6, 265-271 (1962).

[2] Scott, F., Phot. Sci. and Engr. 9, 248-251 (1965).

[3] Offner, A., Phot. Sci. and Engr. 9, 240-243 (1965).

[4] Shack, R. V., J. Opt. Soc. Am. 46, 755-757 (1965).

[5] Rosenau, M. D., Phot. Sci. and Engr. 9, 248-251 (1965).

[6] Shack, R. V., Appl. Opt. 3, 1171-1181 (1964).

[7] Rosenau, M. D., Scott, F., and Thiessen, W. F., Photo. Sci. and Engr. 7, 92-95 (1963).

[8] Lamberts, R. L, J. Opt. Soc. Am. 49, 425-428 (1959)

[9] Selwyn, E. W. H., J. Phot. Sci. 7, 138-147 (1959).

[10] Schade, O. H., J.S.M.P.T.E. 73, 81-119 (1964).

[11] Watt, F. J. B. and Steel, B. G., J. Phot. Sci. 12, 34-46 (1964).

[12] Scott, R. M., Phot. Sci. and Engr. 9, 261-262 (1965).

[13] Scott, F., Phot. Sci. and Engr. 10, 49-52 (1966).

[14] Baker, J. G., U. S. Patent 3,039,361 (June 19, 1962).

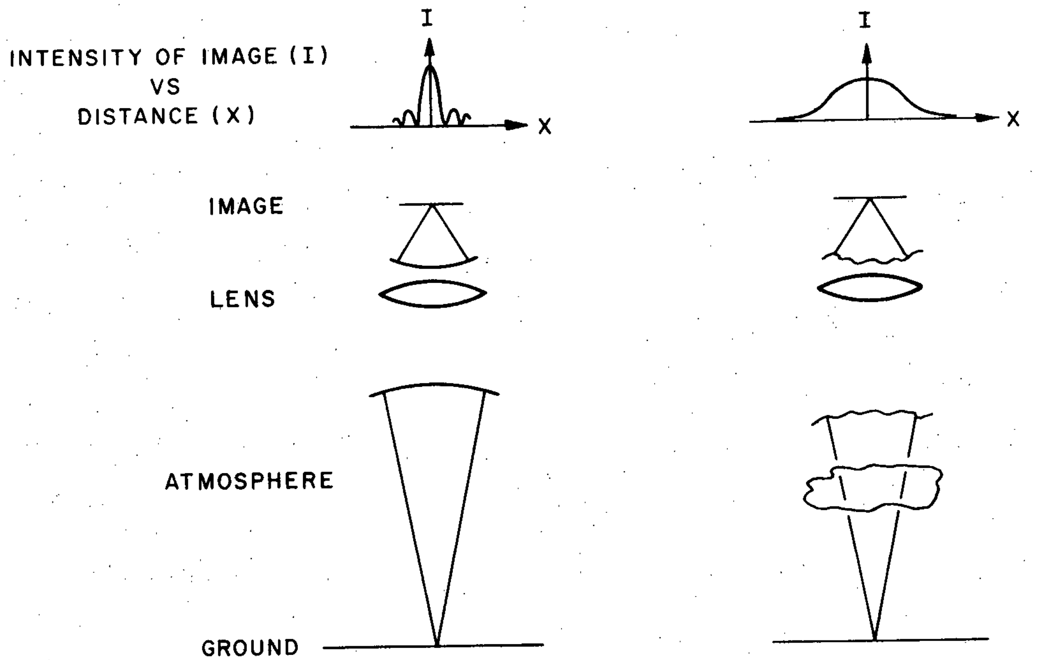
[15] Rimmer, M. P. and Shannon, R. R., J. Opt. Soc. Am. 55, 1570 (1965).

[16] Rosenau, M. D., Appl. Opt. 3, 29-34 (1964).

[17] Waidelich, J. A., J. Opt. Soc. Am. 55, 1589 (1965).

[18] Scott, F, Scott, R. M., and Shack, R. V., Phot. Sci. and Engr. 7, 345-349 (1963).

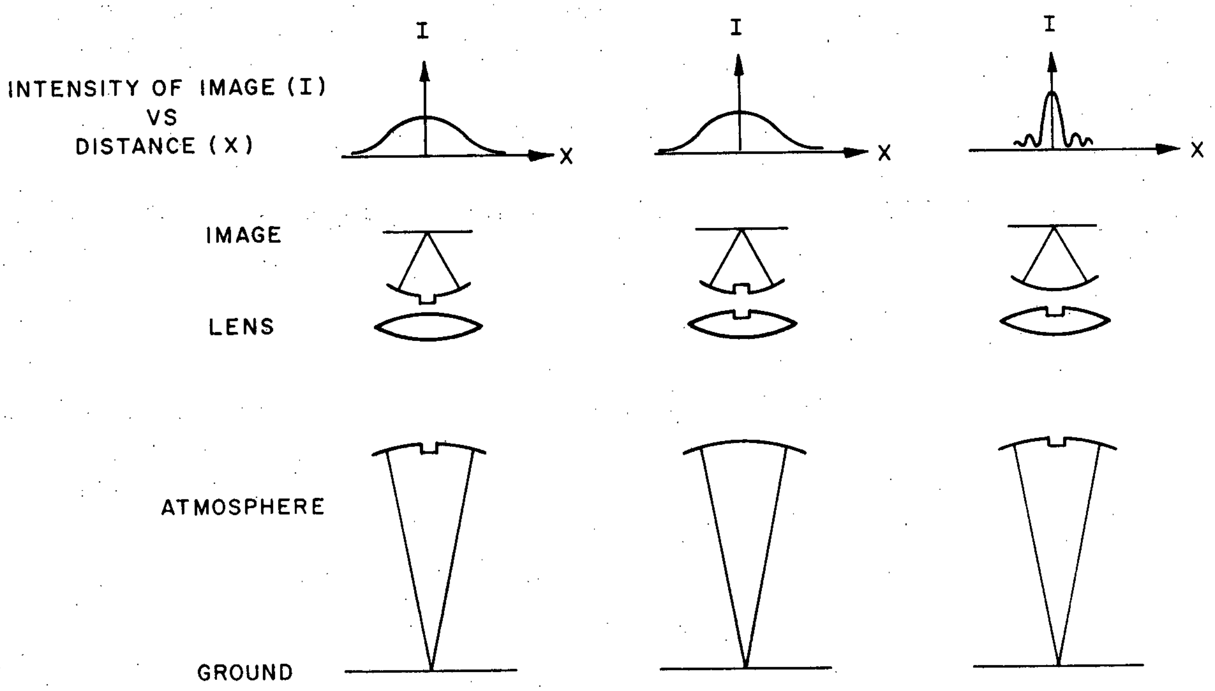
[19] Rosenau, M. D., "Image Evaluation by Edge Gradient Analysis", paper presented at Soc. Phot. Instr. Engrs. 11th Annual Symposium, St. Louis, 22 Aug. 1966.



(A)
PERFECT SYSTEM,
HOMOGENEOUS ATMOSPHERE

(B)
PERFECT SYSTEM,
TURBULENT ATMOSPHERE

FIGURE 1a. OPTICAL WAVEFRONTS



(C)
BAD ATMOSPHERE
GOOD LENS
BAD IMAGE

(D)
GOOD ATMOSPHERE
BAD LENS
BAD IMAGE

(E)
BAD ATMOSPHERE
BAD LENS
GOOD IMAGE

FIGURE 1b. OPTICAL WAVEFRONTS

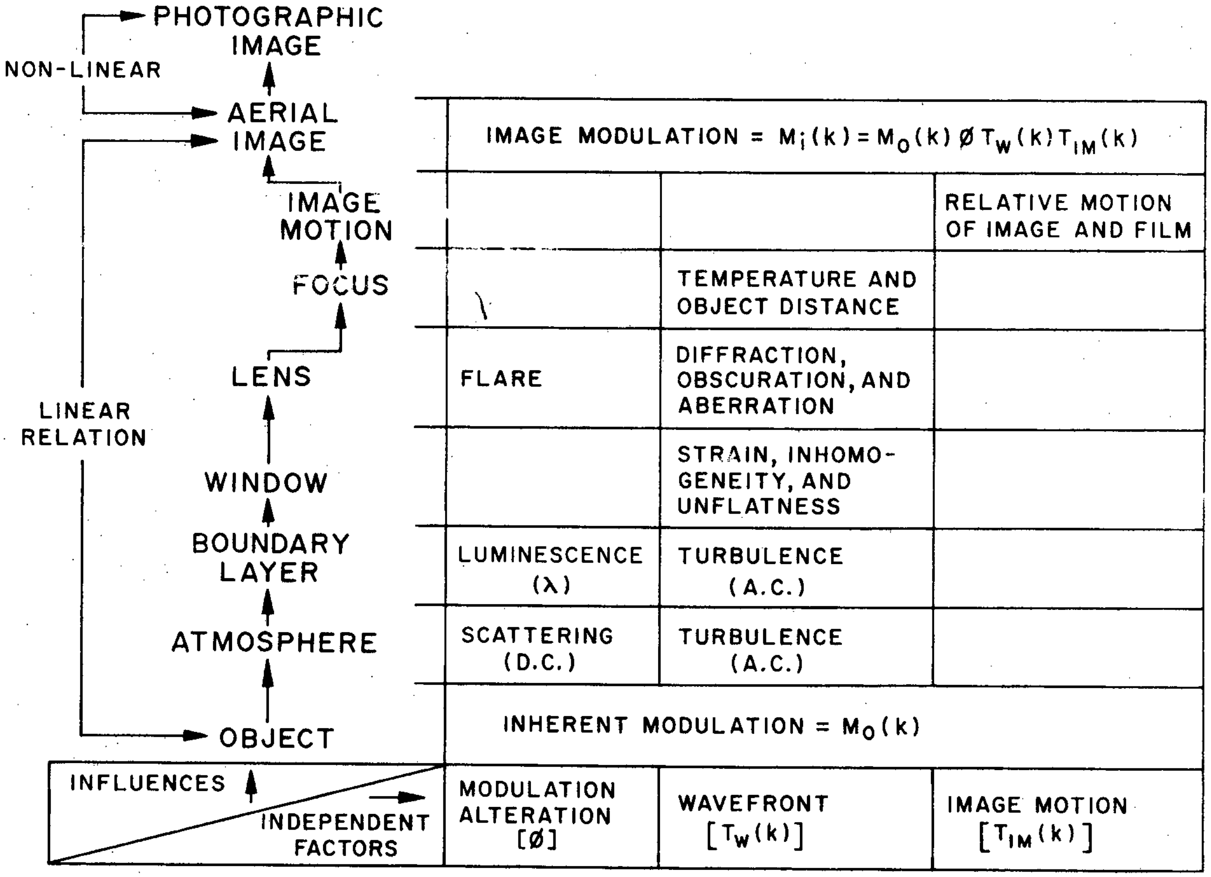
$\Delta(x', y')$ = Wavefront distance at point x', y' in exit pupil from spherical wavefront of radius f

$$G(x', y') = e^{-\frac{2\pi i}{\lambda}\Delta(x', y')} \equiv \text{PUPIL FUNCTION}$$

$$T\left(\frac{x}{\lambda f}, \frac{y}{\lambda f}\right) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} G(x'+x, y'+y)\, G^{*}(x', y')\, dx\,dy$$

$$\equiv \text{OPTICAL TRANSFER FUNCTION}$$

FIGURE 2. DEPENDENCE OF OPTICAL TRANSFER FUNCTION ON WAVEFRONT



INFLUENCES ↑ / INDEPENDENT FACTORS →	MODULATION ALTERATION [$\emptyset$]	WAVEFRONT [$T_W(k)$]	IMAGE MOTION [$T_{IM}(k)$]
AERIAL IMAGE	IMAGE MODULATION = $M_i(k) = M_0(k)\,\emptyset\,T_W(k)T_{IM}(k)$		
IMAGE MOTION			RELATIVE MOTION OF IMAGE AND FILM
FOCUS		TEMPERATURE AND OBJECT DISTANCE	
LENS	FLARE	DIFFRACTION, OBSCURATION, AND ABERRATION	
WINDOW		STRAIN, INHOMOGENEITY, AND UNFLATNESS	
BOUNDARY LAYER	LUMINESCENCE (λ)	TURBULENCE (A.C.)	
ATMOSPHERE	SCATTERING (D.C.)	TURBULENCE (A.C.)	
OBJECT	INHERENT MODULATION = $M_0(k)$		

FIGURE 3. THE AERIAL PHOTOGRAPHIC PROCESS

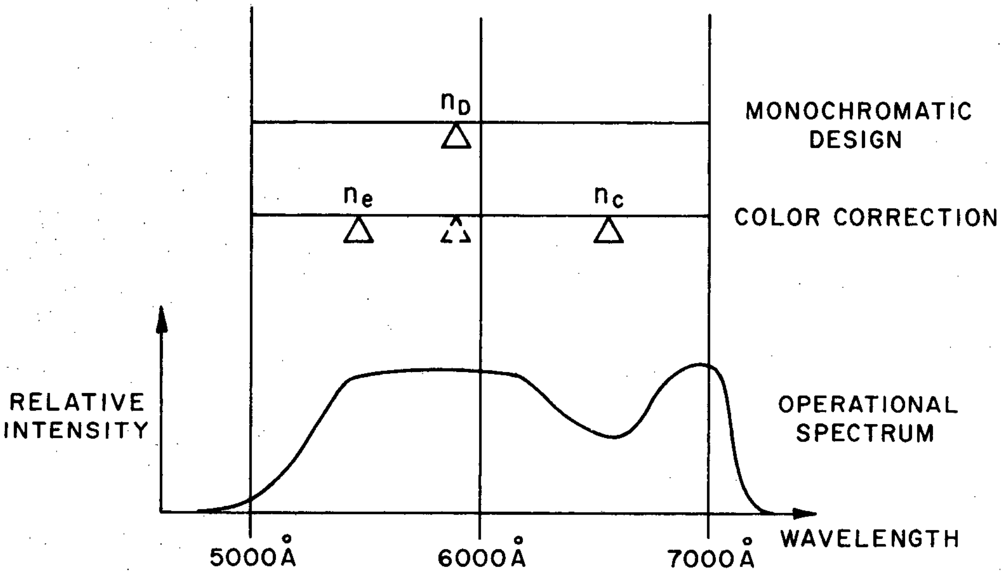


FIGURE 4. AERIAL LENS DESIGN AND A TYPICAL FLIGHT SPECTRUM

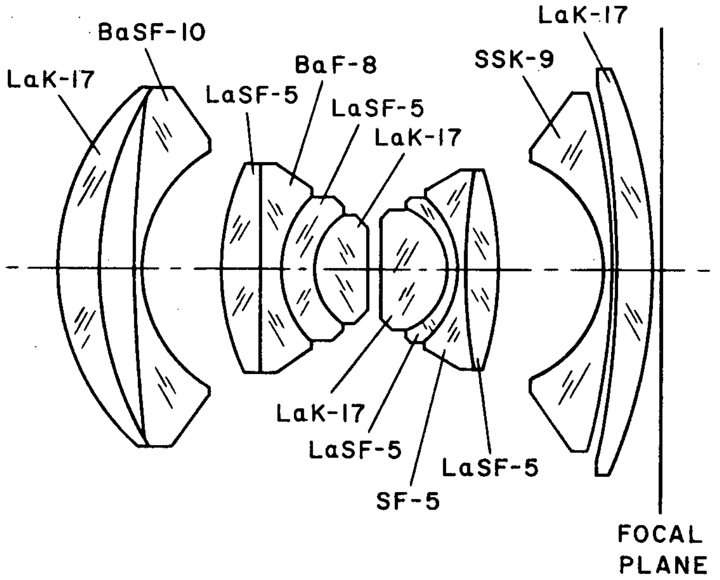
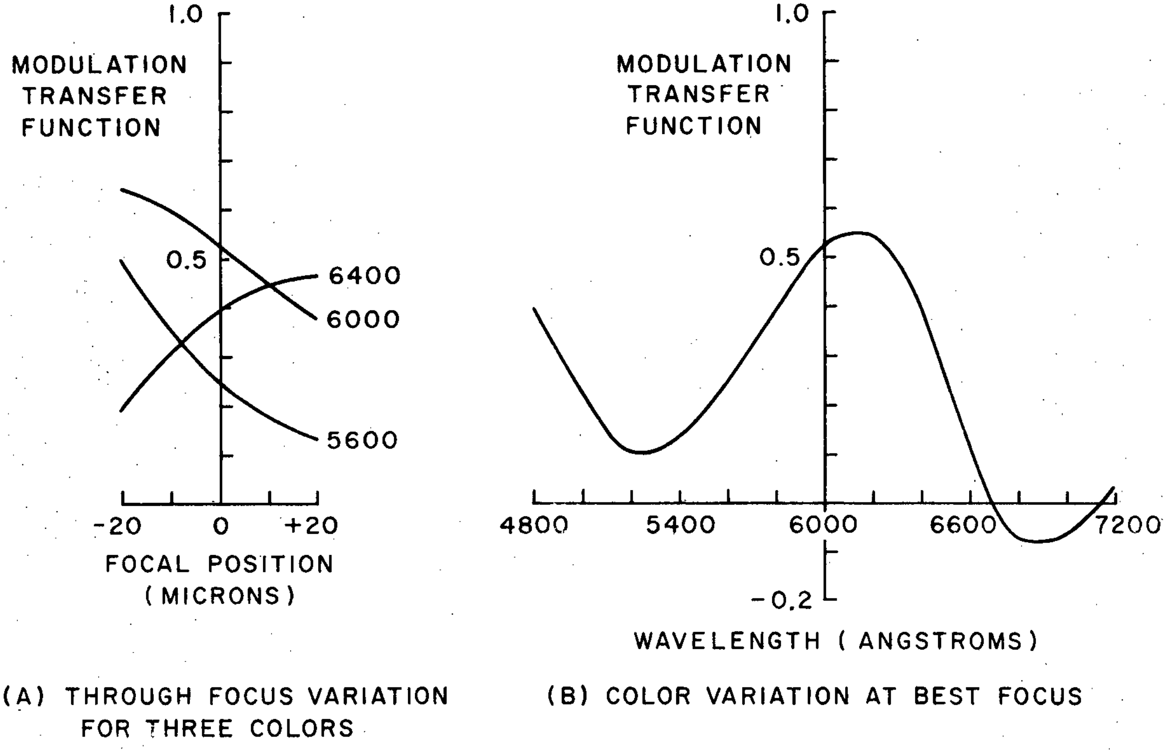


FIGURE 5. GEOCON LENS



(A) THROUGH FOCUS VARIATION FOR THREE COLORS

(B) COLOR VARIATION AT BEST FOCUS

FIGURE 6. MONOCHROMATIC MODULATION TRANSFER FUNCTIONS, ON-AXIS, AT SPATIAL FREQUENCY OF 60 CY/MM

1. RAY TRACE GIVES WAVEFRONT SHAPE IN EXIT PUPIL.
2. WAVEFRONT SHAPE GIVES PUPIL FUNCTION.
3. AUTOCORRELATION OF PUPIL FUNCTION GIVES REAL AND IMAGINARY PARTS OF MONOCHROMATIC OPTICAL TRANSFER FUNCTION.
4. WEIGHTED ADDITION AND NORMALIZATION OF MONOCHROMATIC REAL AND IMAGINARY PARTS GIVES REAL AND IMAGINARY PARTS OF POLYCHROMATIC OPTICAL TRANSFER FUNCTION.

FIGURE 7. STEPS IN COMPUTING MONOCHROMATIC OPTICAL TRANSFER FUNCTIONS

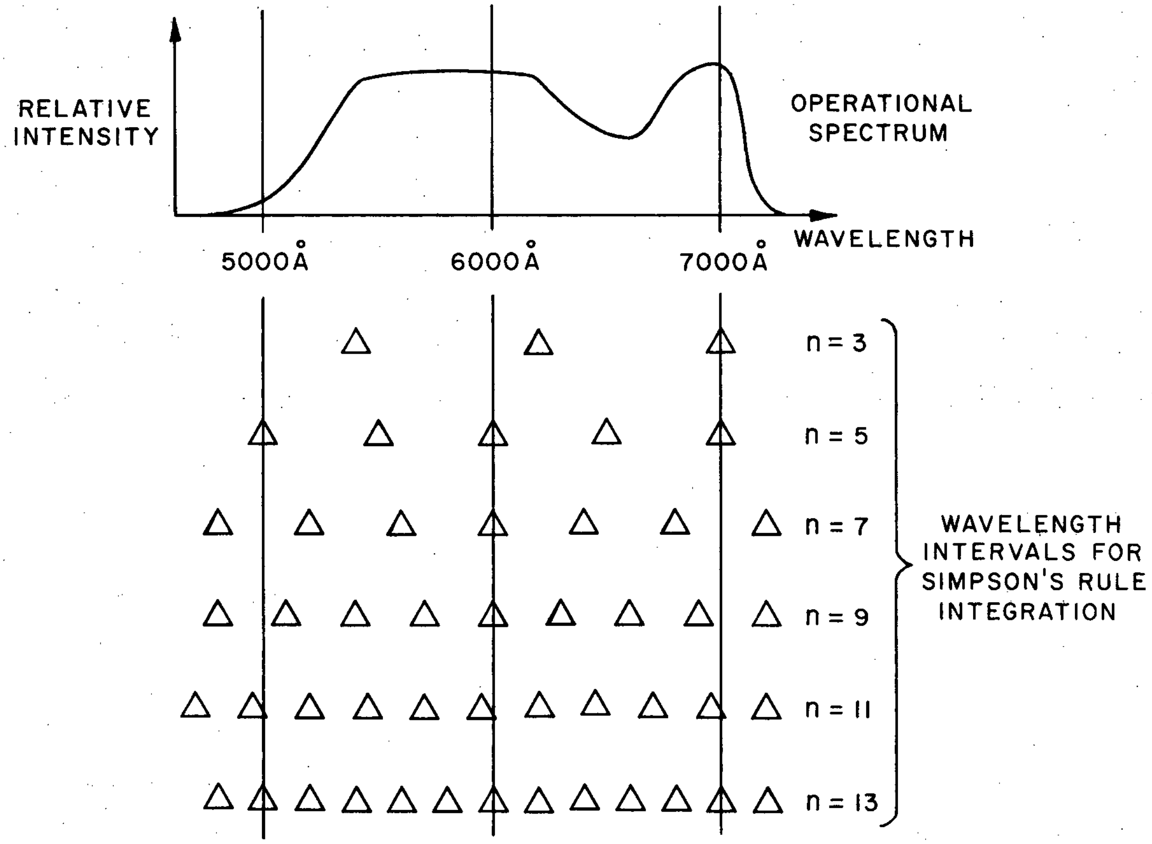


FIGURE 8. APPROXIMATION OF CONTINUOUS SPECTRUM

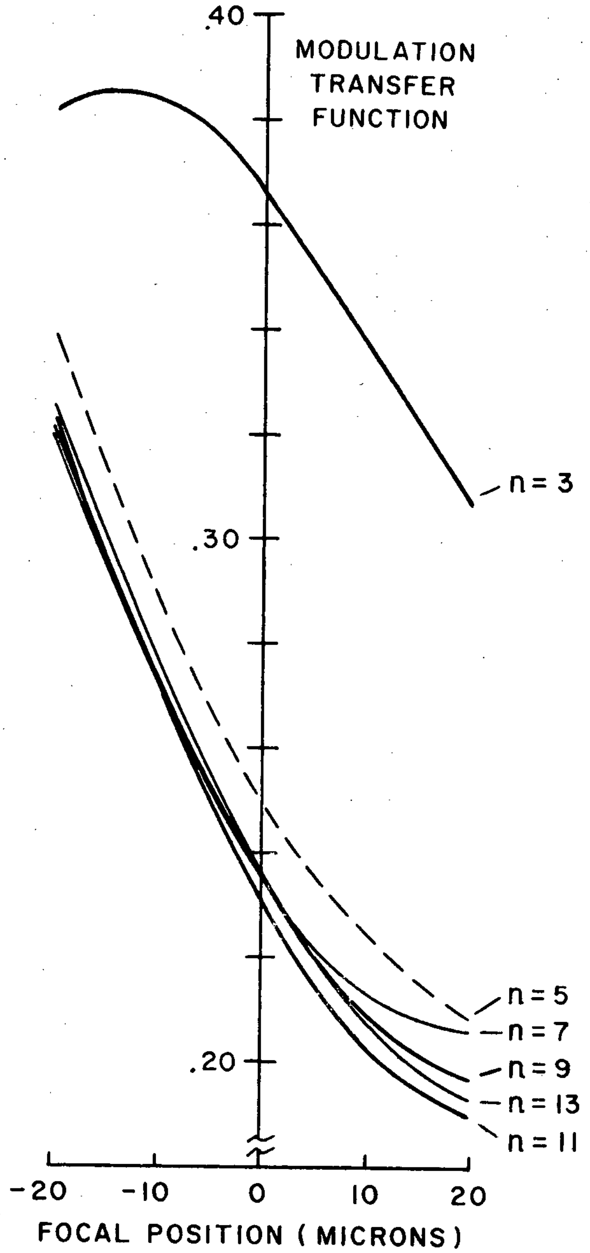
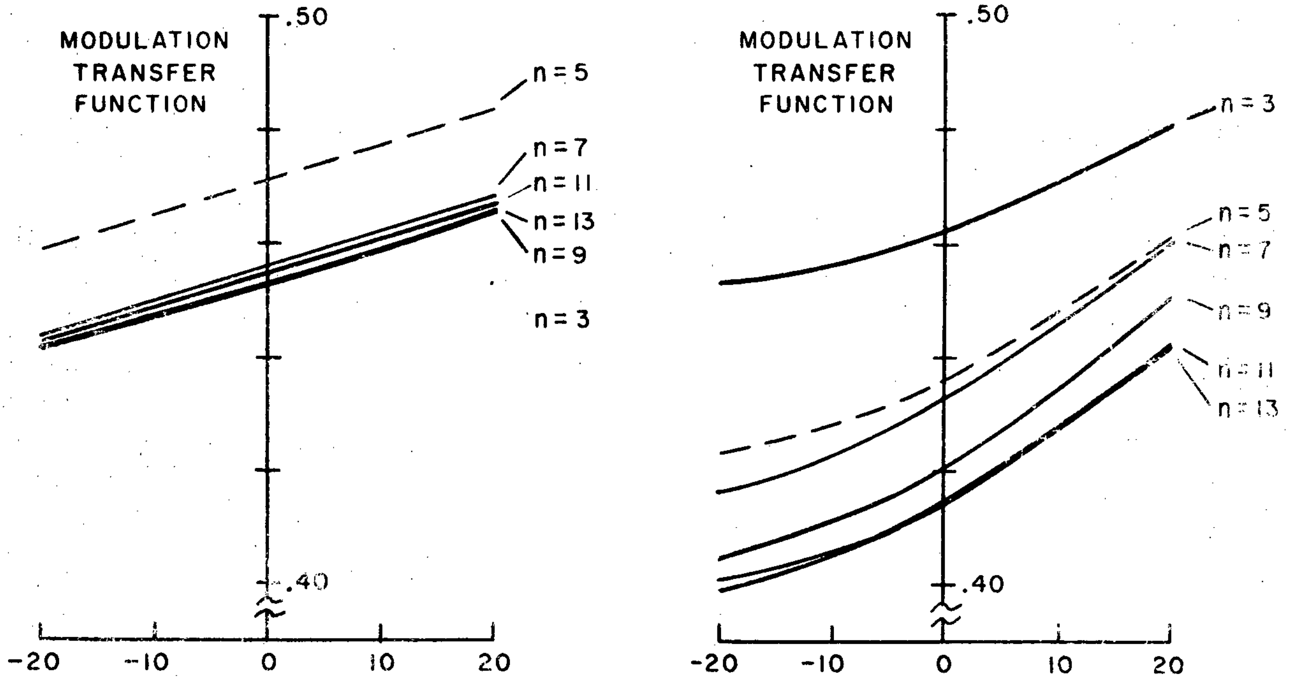


FIGURE 9. POLYCHROMATIC MODULATION TRANSFER FUNCTIONS, ON AXIS, AT SPATIAL FREQUENCY OF 60 CY/MM, FOR DIFFERENT APPROXIMATIONS OF THE OPERATIONAL SPECTRUM



(A) RADIAL (B) TANGENTIAL

FIGURE 10. POLYCHROMATIC MODULATION TRANSFER FUNCTIONS, 28.7 DEGREES OFF-AXIS, AT SPATIAL FREQUENCY OF 20 CY/MM, FOR DIFFERENT APPROXIMATIONS OF THE OPERATIONAL SPECTRUM

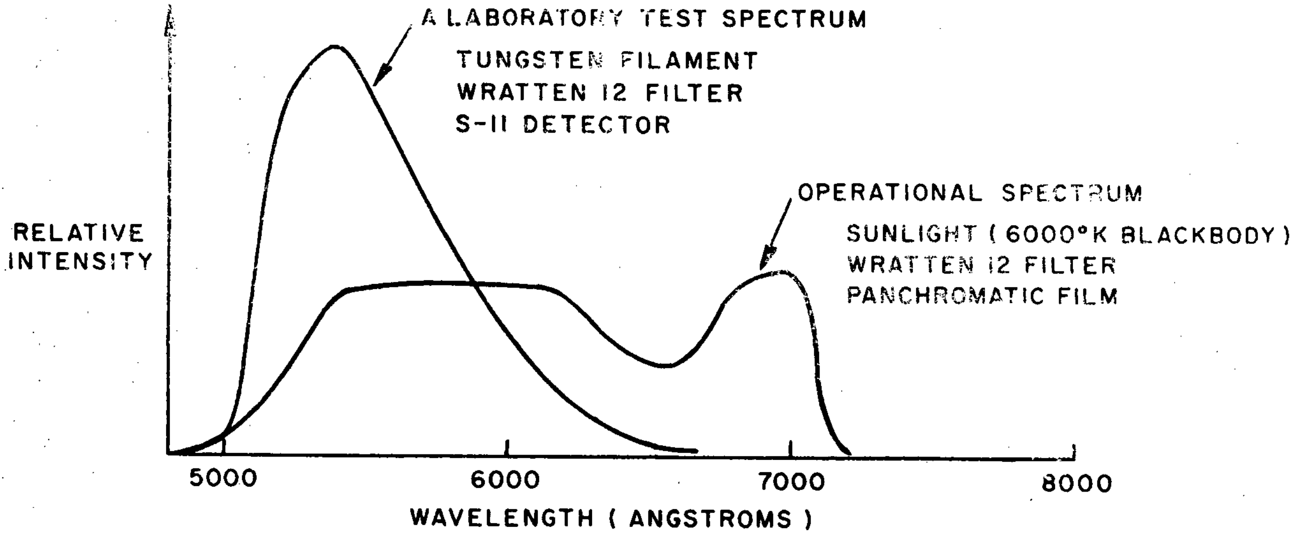


FIGURE 11. TWO SPECTRA

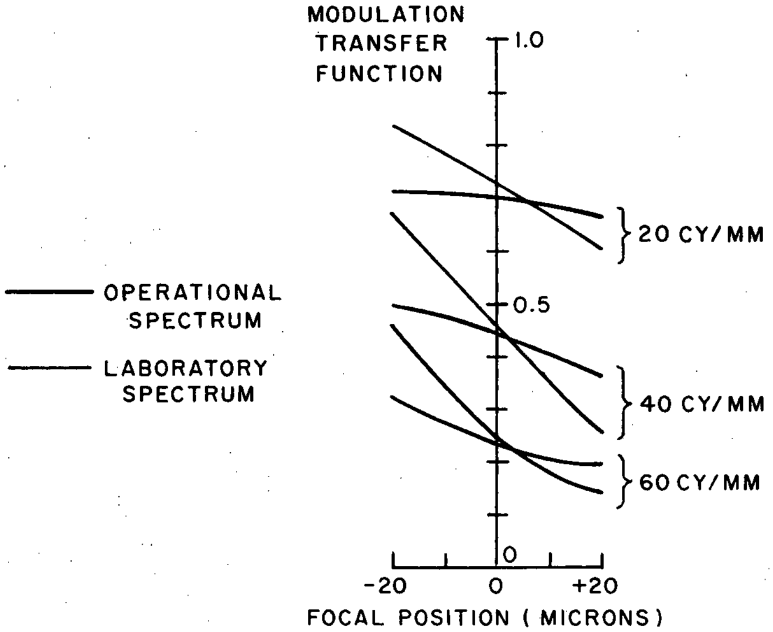


FIGURE 12. POLYCHROMATIC (n = 13) MODULATION TRANSFER FUNCTIONS, ON-AXIS, FOR SPECTRA OF FIGURE 3-8

PURPOSE OF PREDICTION REQUIREMENTS	SELECT AMONG CANDIDATE PHOTO-OPTICAL SYSTEMS	MAKE INTELLIGENT DESIGN "TRADE-OFFS"	SPECIFY ACCEPTANCE CRITERIA
FIXED SPECIFICATION	TARGET FORM GENERAL CAMERA FORM	TARGET FORM SPECIFIC CAMERA FORM	TARGET FORM ACTUAL CAMERA ZERO IMAGE MOTION BEST FOCUS
ASSUMPTIONS NEEDED	IMAGE MOTION FOCUS DISTRIBUTION OF IMAGE LOCATIONS AND ORIENTATIONS	IMAGE MOTION FOCUS	NONE
ITEMS WITH VARIANCE REQUIRING PROBABILITY TREATMENT	IMAGE MOTION FOCUS ATMOSPHERE (IF DIFFERENT FOR CANDIDATES) FILM	IMAGE MOTION FOCUS	RESOLUTION MEASUREMENT TECHNIQUE

FIGURE 13. PREDICTION CONSIDERATIONS

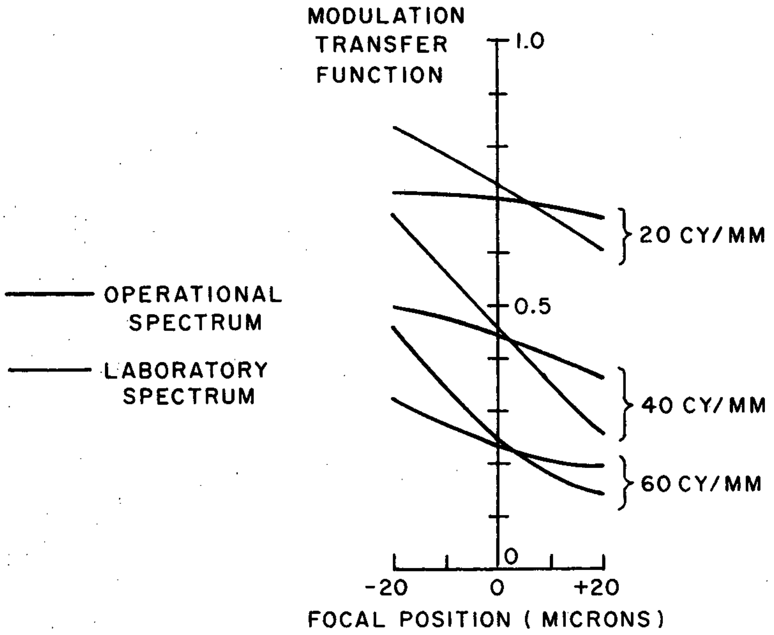


FIGURE 12. POLYCHROMATIC (n = 13) MODULATION TRANSFER FUNCTIONS, ON-AXIS, FOR SPECTRA OF FIGURE 3-8

PURPOSE OF PREDICTION REQUIREMENTS	SELECT AMONG CANDIDATE PHOTO-OPTICAL SYSTEMS	MAKE INTELLIGENT DESIGN "TRADE-OFFS"	SPECIFY ACCEPTANCE CRITERIA
FIXED SPECIFICATION	TARGET FORM GENERAL CAMERA FORM	TARGET FORM SPECIFIC CAMERA FORM	TARGET FORM ACTUAL CAMERA ZERO IMAGE MOTION BEST FOCUS
ASSUMPTIONS NEEDED	IMAGE MOTION FOCUS DISTRIBUTION OF IMAGE LOCATIONS AND ORIENTATIONS	IMAGE MOTION FOCUS	NONE
ITEMS WITH VARIANCE REQUIRING PROBABILITY TREATMENT	IMAGE MOTION FOCUS ATMOSPHERE (IF DIFFERENT FOR CANDIDATES) FILM	IMAGE MOTION FOCUS	RESOLUTION MEASUREMENT TECHNIQUE

FIGURE 13. PREDICTION CONSIDERATIONS

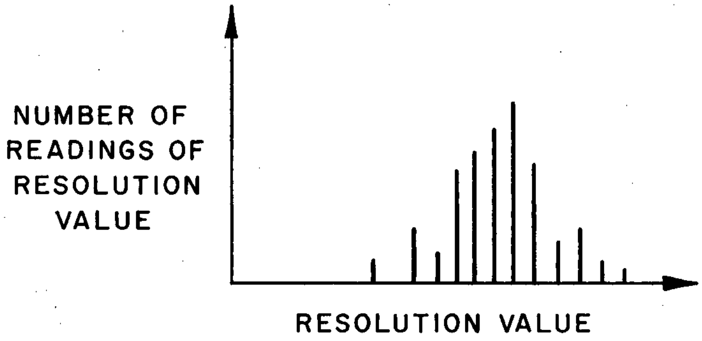


FIGURE 14. RESOLUTION VARIATION

CAUSE \ TARGET TYPE	EDGE GRADIENT	US MILITARY STANDARD TRI-BAR
LACK OF "GROUND TRUTH"	OBJECT WAS NOT A SHARP EDGE	
CONTRAST VARIATION		PAINT DETERIORATION OR ATMOSPHERIC SCATTERING
FILM VARIATION	TRANSFER FUNCTION	MODULATION DETECTABILITY
MEASUREMENT	MICRODENSITOMETER FOCUS, SLIT ALIGNMENT AND DRIVE ACCURACY; TRANSMISSION-EXPOSURE CONVERSION; COMPUTATIONAL TECHNIQUE.	DIFFERENT READERS AND MICROSCOPES; READER CONSISTENCY.

FIGURE 15. CAUSES OF RESOLUTION VARIATION, OTHER THAN CAMERA SYSTEM

(1) SOURCES OF POOR IMAGE QUALITY

NATURE OF IMAGE	PRIME CAUSE
ROTATIONALLY SYMMETRICAL	RANDOM WAVEFRONT DISTORTION FOCUS SPHERICAL ABERRATION
NON-ROTATIONALLY SYMMETRICAL	IMAGE MOTION ASTIGMATISM FOCUS (NON-ROUND PUPIL)
DOUBLED	VIBRATION WINDOW SEAM IN PRESSURIZED CAMERA BAY BENT MIRROR

(2) IS THE MAGNITUDE OF POSTULATED CAUSE REASONABLE FOR THE SYSTEM ?

FIGURE 16. FAULT DIAGNOSIS