Funds for this work were supplied by Air Force Cambridge Research Laboratories, the National Science Foundation, and the National Aeronautics and Space Administration.

References

1. Albritton, D. L., L. C. Young, H. D. Edwards, and J. L. Brown, "Position Determination of Artificial Clouds in the Upper Atmosphere," PHOTOGRAMMETRIC ENGINEERING, September 1962, p. 608.
2. Chauvenet, W., *A Manual of Spherical and Practical Astronomy*, Vol. II (Dover, 1960), Table II, p. 572.
3. Jones, B. L., "Photogrammetric Refraction Angle: Satellite Viewed from Earth," *Journal of Geophysical Research*, April 1961, Vol. 66, No. 4, p. 1135.
4. Vitro, *Instruction Manual KLX 1639*, "Operation and Maintenance, K-24 Camera" (1954), p. 27.

The Optical Specification of Photographic Viewers

MILTON D. ROSENAU, JR., *Senior Physicist,*
The Perkin-Elmer Corp.,
Norwalk, Conn.

ABSTRACT: *The modulation transfer function of optical instruments to view or enlarge photographic transparencies are determinable from a knowledge of the eye's modulation requirement and the amount of modulation and granularity on the transparency. Two hypothetical cases illustrate the specification of the required performance of a viewer or enlarger. It is concluded that the modulation transfer function of viewers and enlargers should be very high at all the spatial frequencies up to the limiting resolution contained in the transparency.*

Introduction

For photography which is viewed by means of an optical system or is optically enlarged, it is desirable to have a rational approach to specify the required optical performance. Any text on optics gives the basis on which magnification and field of view can be specified, but the resolution performance is not covered. In this discussion, it is shown how the modulation transfer function analysis commonly applied to the photographic acquisition process can be extended to viewers.[1–3] The benefit of this approach is that it is based on the physical processes involved, that it has been proven accurate for cameras, and that it is easy to apply to the viewing of any particular photography.

In what follows, the method will be explained and illustrated with hypothetical examples. While these are meant to be physically reasonable cases, other workers are cautioned to extrapolate with care, or preferably to apply the method exactly to any photography for which they wish to specify the performance of viewers.

Approach to Problem

General

Aerial photographs are obtained by cameras which, in airborne operation, have modulation transfer functions, $T(k)$, similar to that shown in Figure 1; these functions usually decrease steadily as the spatial frequency, k, increases. Such cameras will photograph objects, for which the Fourier components will have all possible modulations (contrasts), M_0, from high to very low. Consequently, the corresponding modulation in the exposure (aerial) image which impinges on the emulsion, M_A, will range from high to very low since

$$M_A = T(k)M_0$$

Even for high-contrast objects, for which $M_0=1$, M_A, decreases to very low values at high spatial frequencies because $T(k)$, decreases.

For the image of the Fourier component of an object to be resolvable on the film, M_A must equal or exceed a modulation detectability limit, M_D.[4–6] In general, M_D is a

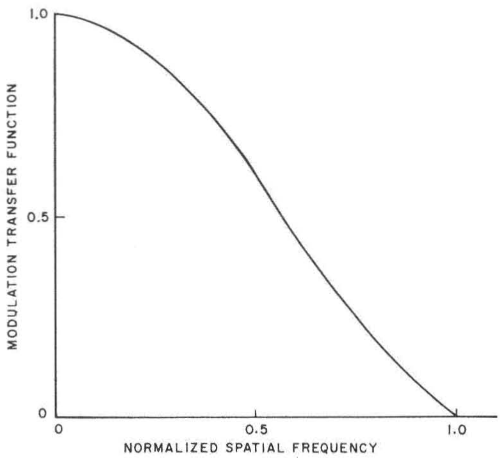

FIG. 1. Typical modulation transfer function of airborne camera.

function of the shape of the object, the granularity of the film, and the spatial frequency. Selwyn[7] has shown the eye to require $M_D \geq 0.032$ for long lines on grainless film; for USAF 1951 targets,[8] the relation is more complicated;[4] and for other shapes, still other values of M_D are required.

After the latent image is developed, the transilluminated negative will have a modulation, M_T. The useful portion of this modulation is that in which the signal modulation, M_A, exceeds the noise modulation, M_D. This useful portion of modulation is then reduced by the transfer function of the viewer (or enlarger), and only those objects for which the resulting modulation still exceeds the eye's detectability limit will be resolved. As has been shown previously,[9] the relation of M_T and M_A is complicated, and M_T is sometimes greater than M_A, sometimes equal to M_A, and sometimes less than M_A. M_T and M_A will be assumed here to be numerically equal, which is approximately correct if a wide range of exposures is probable. The analysis for cases when M_T is not equal to M_A is analogous to what follows.

Further, in what follows, it is assumed that the object shapes are such that $M_D = 0.04$, which is probably rather reasonable for many cultural shapes. (However, the eye's modulation limit is not yet well-established and is certainly variable.) Also, for illustrative purposes, $T(k)$ of aerial photography is assumed to be gaussian, which is a reasonable approximation to actuality.

CASE 1

In Figure 2, the modulation requirement of the eye, assumed 0.04, is shown. The upper curve is the exposure modulation available from objects with $M_0 = 1$ where $T(k)$ is assumed gaussian. The spatial frequency is normalized in such a manner that it has a value of 1.0 when $M_A = 0.04$ for $M_0 = 1$. Thus, this would be the spatial frequency cited as the aerial camera's limiting resolution under the best of conditions—100 cycles/millimeter for instance. Similar curves have been drawn for M_A when $M_0 = 0.72$ (medium-contrast), and $M_0 = 0.23$ (low-contrast).

One well-known fact is immediately obvious—the low-contrast resolution-limit is lower than the high. For this illustrative case, it is 75 per cent of the high-contrast spatial frequency limit, that is 75 cycles/millimeter if the latter is 100 cycles/millimeter.

Now, recalling that the eye needs $M_D \geq 0.04$, it is clear that the viewer's modulation-transfer function, $T_v(k)$, must be

$$T_v(k) \geq \frac{0.04}{M_T}$$

where $M_T = M_A$ is assumed. This is illustrated in Figure 3, where the required modulation-transfer functions of viewers are shown for the low, medium and high-contrast images considered in Figure 2. Also shown is the required modulation-transfer function for a very low contrast ($M_0 = 0.06$) object, illustrating that the viewer requires a high modulation-transfer function at all spatial frequencies. On the same graph, three theoretical (diffraction) limits of incoherently illuminated circular aperture viewers are shown. For example, the upper curve is that

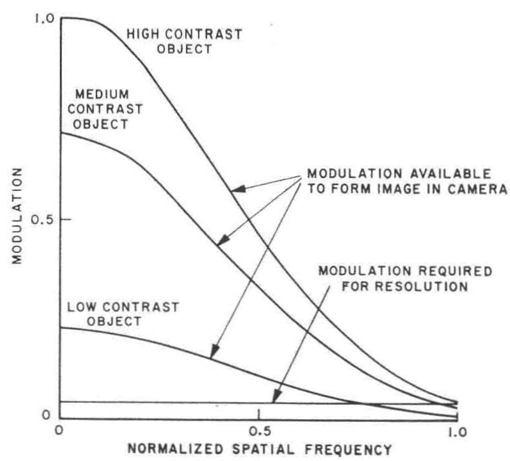

FIG. 2. Available modulation vs. resolution requirement for eye limit of 4 per cent.

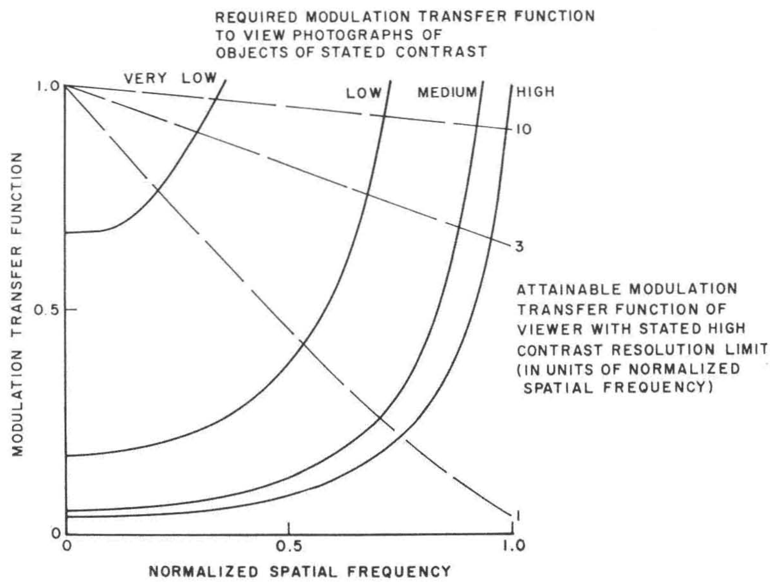

FIG. 3. Required viewer performance compared with attainable performance for eye limit of 4 per cent with grain limited photograph.

modulation-transfer function which could be achieved by a viewer with a high-contrast resolution limit 10 times that of the aerial camera, that is 1,000 cycles/millimeter if the camera limit is 100 cycles/millimeter.

For the particular case illustrated in Figures 2 and 3, a diffraction limited viewer with high-contrast resolution 3 times that of the aerial camera has lost about five per cent of the camera's limiting resolution. It is clear that a viewer with a resolution limit only equal to that of the aerial camera gives up about twenty-five per cent of the available high-contrast resolution.

CASE 2

In this case, the object shapes are assumed to be such that granularity enters into the modulation-detectability limit, and a hypothetical curve is shown in Figure 4. The other curves in Figure 4 are similar to these in Figure 2, normalized in the same manner.

Since a portion of the resolution limit, the granularity modulation, M_G, is also lowered by the viewer's modulation-transfer function, the "noise" modulation, M_N, will be

$$M_N = \{[T_v(k)M_G]^2 + [0.04]^2\}^{1/2}$$

in which the eye's limit is again assumed to be 0.04 and $T_v(k)$ is the modulation transfer-function of the viewer. The "signal" modulation, M_S, will be

$$M_S = T_v(k)M_A$$

where M_A is the aerial image-modulation which is again assumed numerically equal to the modulation of the grainless transilluminated negative.

Thus, to have "signal" exceed "noise," it is required that

$$T_v(k) 3 \frac{0.04}{(M_A^2 - M_G^2)^{1/2}}$$

On this basis, the curves for required viewer performance are shown in Figure 5. Again, theoretically achievable viewer performance is shown.

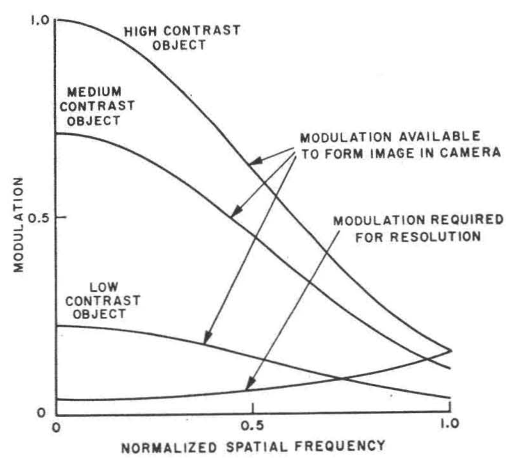

FIG. 4. Available modulation vs. resolution requirement for granularity limit of 15 per cent.

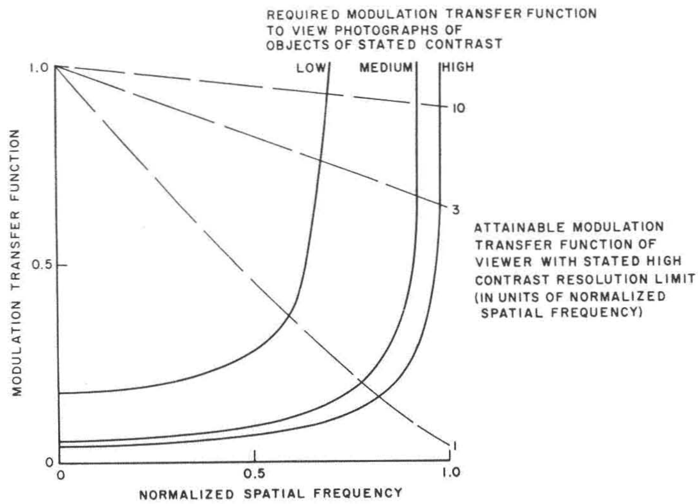

FIG. 5. Required viewer performance compared with attainable performance for eye limit of 4 per cent.

CONCLUSIONS

It is clear that the simple kind of analysis illustrated in this discussion can be applied to the photography of any object, permitting precise specification of the optical transfer function of the viewer (or enlarger). In any actual case the numerical results will differ somewhat from the illustrative values, but the general viewer requirement of a high modulation transfer function at all spatial frequencies up to the limiting resolution of the aerial camera is invariant. As a general rule of thumb, it would seem that the high-contrast resolution limit of the viewer should be perhaps five times that of the aerial camera because the modulation-transfer function of most viewers will not approach the diffraction limit used in the illustrations. As a lower bound, the viewer-limit probably should be twice the camera-limit to avoid prohibitive losses, and as an upper bound, it appears that very little is to be gained if the viewer-limit exceeds the camera-limit by more than a factor of ten.

A related consequence of this analysis is that cameras with very high spatial frequency resolution place even greater demands on viewers; and since there is a practical limit for viewers, an even lower limit exists for aerial cameras.

ACKNOWLEDGMENT

Helpful comments were made by R. C. Babish and R. E. Hufnagel.

REFERENCES

1. Scott, R. M. *Phot. Sci. Eng.*, *3*, 201 (1959).
2. Perrin, F. H. J.S.M.P.T.E., *69*, 151 and 239 (1960).
3. Rosenau, M. D. *Phot. Sci. Eng.*, *6*, 265 (1962).
4. "The Practical Application of Modulation Transfer Functions," Chap. 4 (The Perkin-Elmer Corporation, Norwalk, Conn., 1963).
5. Brock, G. C., W. L. Attaya, and E. P. Myskowski, "Study of Image-Evaluation Techniques," Itek Report 9048-1 (1962), ASTIA Doc. 286-488.
6. Campbell, C. E. PHOTOGRAMMETRIC ENGINEERING, XXVIII, 466 (1962).
7. Selwyn, E. W. H. *Proc. Phys. Soc.* (London), *55*, 286 (1943).
8. Mil Std 150A, 12 May 1959, Photographic Lenses.
9. Scott, F. and M. D. Rosenau, *Phot. Sci. Eng.*, *5*, (1961).