O. G. Malan
National Physical Research Laboratory
Pretoria, South Africa

Color Balance of Color-IR Film

A simple semi-quantitative method for the adjustment yields reproducible results without a densitometer.

Introduction

Although color-infrared film or *false color* film has been used extensively for vegetation and other resources surveys for more than a decade, there still seems to be considerable controversy about its usefulness for these purposes.[1] The unqualified statement that certain features could not be distinguished by this type of film is only too often heard or read.

These disagreements and doubts about the utility of color-infrared film is most probably due to the fact that often the photographic technique employed did not exploit the full capabilities of the medium. The fact that the optimum color balance required depends on the subject investigated and could be obtained by judicious filtering was recognized by Fritz in 1967[4]. More recently Pease and Bowden[5] have shown how the optimum color balance for high-altitude photographs could be obtained in a similar manner. The fact that these procedures are largely based on trial-and-error methods (a color balance-exposure series of 69 mentioned by Fritz!) might have delayed their more widespread acceptance.

During experiments designed to provide high-altitude aerial photographic support to the ERTS-1 program, a semi-quantitative method for estimating a suitable filter combination and exposure factor was developed. This method yielded reproducible results. The procedure is within the capabilities of users who do not have access to sophisticated photographic procedures such as densitometric or special photographic techniques. This procedure could, furthermore, also accommodate color shifts due to non-ideal processing conditions, batch-to-batch variations in film quality and gradual aging of the film.

The only prerequisites for this procedure are consistent (though non-perfect) processing conditions, reasonable stocks of film of the same characteristics and not too rapid aging conditions.

Abstract: *A semi-quantitative method is described for the selection of a suitable combination of Kodak Wratten or Color Compensating filters and the exposure factor required for optimum color balance in color-infrared film. This method does not require sophisticated photographic techniques or equipment, the only prerequisite being consistent processing conditions and a reasonable stock of film with similar characteristics. Tables are presented to facilitate the estimation of the color balance and exposure factors of filter combinations.*

Theory

The sensitivity of, for example, the yellow-forming layer of color-infrared film is defined[3] as

$$S_Y(\lambda) = 1/E_y(\lambda) \qquad (1)$$

where $E_y(\lambda)$ is the energy density of monochromatic blue radiation at wavelength λ required to produce an optical density of 1.0 in the yellow layer.

If the film is exposed through one or more filters with a transmission of $F_i(\lambda)$ the quantity

$$1/\left(\int_0^\infty S_y(\lambda)\, F_1(\lambda)\, F_2(\lambda) \cdots F_n(\lambda)\, d\lambda\right) \qquad (2)$$

is equivalent to the energy density produced by a *white* energy spectrum containing constant energy per wavelength unit (constant spectral energy density).

The quantity

$$E_y = -log_{10} \int_0^\infty S_y(\lambda) F_1(\lambda) F_2(\lambda) \cdots F_n(\lambda)\, d\lambda \qquad (3)$$

is therefore equivalent to the relative log exposure required to produce an optical density 1.0 in the yellow layer.

The relative log sensitivity for blue radiation

$$\sigma_y = log_{10} \int_0^\infty S_y(\lambda) F_1(\lambda) F_2(\lambda) \cdots F_n(\lambda) d\lambda \qquad (4)$$

is a more useful measure in practice.

Similar parameters σ_m and σ_c may be defined for the magenta and cyan layers, giving respectively the relative log sensitivities to red and infrared radiation.

The first three columns of Table 1 give the values of σ_y, σ_m and σ_c for Kodak Aerochrome Infrared Film 2443 in conjunction with different combinations of commonly used Kodak Wratten and Color Compensating Filters. These values were calculated according to Equation 4, using the manufacturer's data[2] on the spectral sensitivity $S(\lambda)$ of Kodak Aerochrome Infrared Film 2443 and filter transmissions $F_i(\lambda)$ as measured on a Beckmann Model DK Recording Spectrophotometer. The transmission curves for some filters are given in Figure 1. Integration was performed numerically between 460 and 900 nm (the limits between the cut-on of the minus-blue filters and the long wavelength sensitivity of the film) at 10-nm intervals by means of a computer program which facilitated the calculation of the effect of any filter combination. These values may be presented graphically for selected combinations as shown in Figure 2.

The fact that the value of σ_c is about 0.4 units lower than that of σ_y and σ_m upon employing the No. 12 filter, reflects the lower sensitivity of the cyan layer with respect to the magenta and yellow layers[2].

The fourth column of Table 1 also lists

$$\sigma = 1/3\, (\sigma_y + \sigma_m + \sigma_c) \qquad (5)$$

TABLE 1. FILTER COMBINATION EXPOSURE AND COLOR BALANCE PARAMETERS*

Filter or Combination	σ_y	σ_m	σ_c	σ	C_y	C_m	C_c
12	1.96	1.98	1.54	1.83	0.462	0.490	0.048
15	1.91	1.98	1.54	1.81	0.433	0.506	0.061
16	1.77	1.98	1.53	1.76	0.340	0.559	0.101
12 + CC 10M	1.83	1.94	1.49	1.76	0.406	0.518	0.076
12 + CC 20M	1.75	1.93	1.49	1.72	0.362	0.538	0.100
12 + CC 30M	1.64	1.92	1.48	1.68	0.297	0.569	0.134
12 + CC 40M	1.53	1.89	1.47	1.63	0.236	0.593	0.171
12 + 82A	1.82	1.80	1.43	1.69	0.471	0.452	0.077
12 + 82A + CC 10M	1.69	1.76	1.39	1.61	0.415	0.479	0.106
12 + 82A + CC 20 M	1.62	1.75	1.38	1.58	0.371	0.499	0.130
12 + 82A + CC 30M	1.51	1.73	1.37	1.57	0.306	0.529	0.165
12 + 82A + CC 40M	1.40	1.71	1.36	1.49	0.245	0.552	0.203
12 + 82B	1.78	1.74	1.41	1.64	0.467	0.435	0.098
12 + 82B + CC 10M	1.65	1.70	1.36	1.57	0.411	0.462	0.127
12 + 82B + CC 20M	1.57	1.69	1.36	1.54	0.367	0.481	0.152
12 + 82B + CC 30M	1.46	1.67	1.35	1.49	0.302	0.511	0.187
12 + 82B + CC 40M	1.35	1.65	1.34	1.45	0.241	0.534	0.225
12 + 80C	1.62	1.55	1.31	1.50	0.462	0.385	0.153
12 + 80C + CC 10M	1.49	1.50	1.27	1.42	0.406	0.410	0.184
12 + 80C + CC 20M	1.42	1.49	1.27	1.39	0.362	0.429	0.209
12 + 80C + CC 30M	1.31	1.47	1.25	1.35	0.297	0.458	0.245
12 + 80C + CC 40M	1.20	1.45	1.25	1.30	0.236	0.480	0.284
12 + 80B	1.44	1.34	1.24	1.34	0.435	0.335	0.230
12 + 80B + CC 10M	1.31	1.30	1.20	1.27	0.378	0.360	0.262
12 + 80B + CC 20M	1.29	1.28	1.19	1.24	0.333	0.379	0.288
12 + 80B + CC 30M	1.12	1.27	1.19	1.20	0.267	0.407	0.325
12 + 80B + CC 40M	1.02	1.24	1.18	1.15	0.207	0.428	0.365

* $\int_0^\infty S(\lambda) F_1(\lambda) F_2(\lambda) \cdots F_n(\lambda)\, d\lambda$ in units of 10^{-12} m³ erg⁻¹

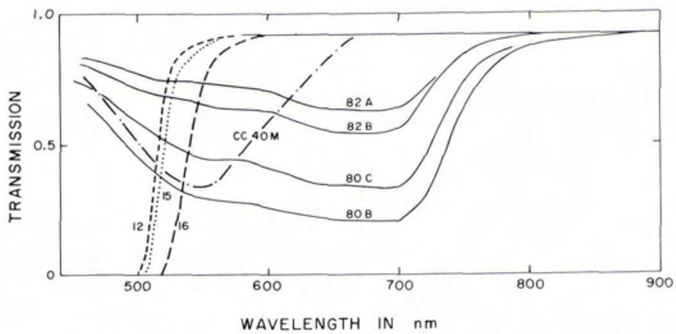

FIG. 1. Transmission curves of some Kodak filters.

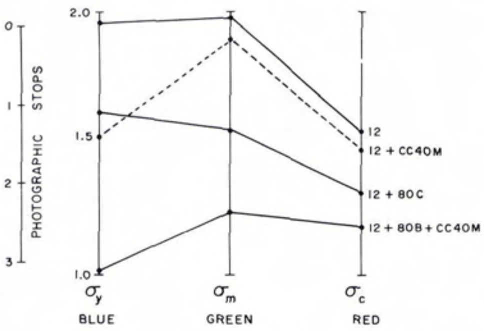

FIG. 2. Bar graph representation of relative log sensitivities for some filter combinations.

which may be used in practice to estimate the exposure. A decrease in σ of 0.30 units necessitates an exposure increase of one photographic stop.

A more convenient way to represent the relative sensitivities of the three layers is to define the parameters

$$C_y = \sigma_y + \tfrac{1}{3} - \sigma \qquad (6a)$$

$$C_m = \sigma_m + \tfrac{1}{3} - \sigma \qquad (6b)$$

$$C_c = \sigma_c + \tfrac{1}{3} - \sigma \qquad (6c)$$

Consequently

$$C_y + C_m + C_c = 1 \qquad (7)$$

only two of these parameters being independently variable.

The physical significance of C_y, C_m and C_c is that they are the corresponding values of σ_y, σ_m and σ_c when the particular filter combination is combined with a neutral density filter to reduce σ to $\frac{1}{3}$.

The values of C_y, C_m and C_c, also listed in the last three columns of Table 1, may be presented graphically in a triangular color-space graph as shown in Figure 3 for some filter combinations.

Diagrams similar to Figure 3 can be constructed on commercially available triangular graph paper by plotting the corresponding values of C_y, C_m and C_c (listed in Table 1 or calculated according to Equations 4 and 6 for other filters) for those filters employed. The required exposure increase in photographic stops, derived from σ in Table 1 (or calculated according to Equation 5) may be indicated by contours as in Figure 3.

In practice it is found that each successive addition of a further filter to the essential minus-blue filter causes a change, $\Delta\sigma$ in σ. These differences are approximately additive. This is due to the fact that only small variations occur in $F_i(\lambda)$ over the range where the product of the particular $S(\lambda)$ with the minus-blue filter curve is non-zero.

Similarly an additional filter causes changes in the values of C_y, C_m and C_c. These differences, ΔC_y, ΔC_m and ΔC_c, are also found to be approximately additive but in a vectorial sense.

Table 2 lists the values of the differences $\Delta\sigma$, ΔC_m and ΔC_c for different filters as well as the values of r and θ, the magnitude and direction of the vector as defined in Figure 3. It can be shown that

$$r^2 = (\Delta C_m)^2 + (\Delta C_m)\ (\Delta C_c) + (\Delta C_c)^2 \qquad (8)$$

$$\text{and } \sin\theta = \sqrt{3}\ \Delta C_m/2r. \qquad (9)$$

Given the values in Table 1 of σ, C_y, C_m and C_c for the minus-blue filters 12, 15 and 16, the corresponding approximate values for any filter combination may be calculated analytically or graphically by the utilization of the difference values in Table 2 (observing the algebraic signs).

Some values of σ, C_m and C_c obtained in this manner are compared in Table 3 with values obtained from exact calculations according to Equations 4, 5, 6a and 6b. The agreement for the first four combinations is almost exact. This is because these values in

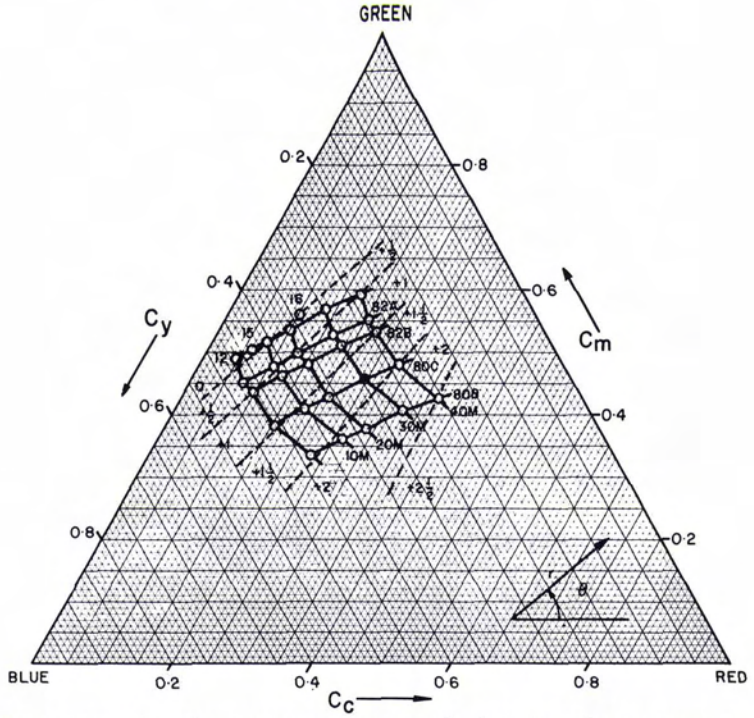

FIG. 3. Triangular color space representation of color balance by the parameters C_y, C_m and C_c. The solid circle, for example, represents the values for the combination 12 + 80C + CC 30M. Dashed contour lines indicate the required increase in exposure in photographic stops. The diagram in the lower right hand corner defines the parameters r and θ

TABLE 2. DIFFERENCES FOR CALCULATION OF APPROXIMATE FILTER COMBINATION PARAMETERS

Filter	$\Delta\sigma$	ΔC_m	ΔC_c	r	θ
82A	−0.14	−0.039	0.030	0.035	−73°
82B	−0.19	−0.057	0.052	0.055	−64°
80C	−0.33	−0.109	0.109	0.109	−60°
80B	−0.48	−0.160	0.188	0.176	−52°
CC 10M	−0.07	0.026	0.029	0.048	28°
CC 20M	−0.10	0.046	0.055	0.088	27°
CC 30M	−0.15	0.075	0.090	0.143	27°
CC 40M	−0.20	0.098	0.129	0.197	26°
CC 10B	−0.12	−0.008	0.026	0.023	−17°
CC 20B	−0.21	−0.021	0.055	0.048	−22°
CC 30B	−0.28	−0.034	0.090	0.079	−22°
CC 40B	−0.34	−0.048	0.126	0.110	−22°
CC 50B	−0.40	−0.063	0.167	0.146	−22°
15-12	−0.02	0.014	0.014	0.024	30°
16-12	−0.07	0.070	0.059	0.112	33°

Table 1 were used to set up Table 2. Good agreement is also found for filter combinations employing a Wratten No. 16 filter which were not used for Table 2. Finally, larger but tolerable disagreement is found for the last two combinations consisting of four filters. The practical utility of such dense combinations is, however, questionable in view of the large exposure factors (more than three stops) involved.

Better estimates for combinations with Wratten 15 and 16 may be obtained by using the corresponding figures in the last two rows of Table 2.

TABLE 3. COMPARISON OF APPROXIMATE AND EXACT CALCULATIONS OF FILTER COMBINATION PARAMETERS

Filter Combination	*Calculation*	σ	C_m	C_c
12 + 82B + CC 30M	approximate	1.49	0.508	0.190
	exact	1.49	0.511	0.187
15 + 82A + CC 40M	approximate	1.47	0.565	0.220
	exact	1.47	0.569	0.219
12 + 80C + CC 10M	approximate	1.43	0.407	0.186
	exact	1.42	0.410	0.184
15 + 80B + CC 20M	approximate	1.23	0.392	0.304
	exact	1.22	0.396	0.307
16 + 80B + CC 10M	approximate	1.21	0.425	0.318
	exact	1.20	0.432	0.331
16 + 82A + CC 40M	approximate	1.42	0.618	0.260
	exact	1.42	0.621	0.263
12 + 82A + 80B + CC 10M	approximate	1.14	0.317	0.295
	exact	1.14	0.311	0.314
15 + 82B + 80B + CC 40M	approximate	0.94	0.387	0.430
	exact	0.96	0.374	0.471

EXPERIMENTAL

In view of the fact that our experience and published as well as unpublished reports indicate that the relative sensitivities of the layers of color-infrared film may vary considerably with emulsion number, as a result of thermal history or with processing conditions, the *absolute* values of the figures in the tables are of limited value. Provided it may be assumed that the changes in sensitivity are caused by vertical shifts in spectral sensitivity curves, the *relative* values may be used to select a set of filters and an exposure factor in order to obtain a desired color balance.

For this purpose a particular batch of raw materials and the processing conditions are *standardized* for a particular subject and set of conditions by means of a limited series of exposures. These might be made with the filter combinations representing the extreme and central values in the color-space diagram Figure 3. Because the filter factors can be estimated from σ to within close limits, a filter combination-exposure series of 10 to 15 exposures may be sufficient to select the optimum color balance for the photographic mission.

Subsequent color balance shifts can be corrected by inspection of Figure 3 and, if necessary, supplemented with additional calculated filter combinations. For increase in red (more infrared sensitivity) a filter shift into the direction $\theta = -30$ is required. For more green (red sensitivity) or blue (green sensitivity) filter shifts in the directions $\theta = 90°$ and $\theta = -150°$, respectively, are required. With experience the value of r required can be estimated with confidence.

In the current program particular attention was paid to high-level photography for which increased infrared sensitivity (more red) is required[5]. The blue-green color balance was also adjusted to an optimum to record the characteristic red soils of the target area in yellow.

Preliminary experiments were undertaken with hand-held 35-mm photography employing readily available and inexpensive 35-mm Kodak Ektachrome Infrared Film. Supplies in batches of 5 rolls were obtained from local dealers and processed commercially by the E-4 process. Filters were mounted in front of the lens.

Although consistent quality was obtained with different processing orders of one batch of film, large variations in color balance were observed with films from different batches. Particularly the first batch of film showed an excessive blue cast, probably due to aging. By following the procedure outlined above, satisfactory photographs could, however, also be obtained with this batch of film.

Full-scale tests were undertaken on Kodak Aerochrome Infrared Film 2443 in a 114-mm format aerial camera with 200-mm lens.

Processing of this format film was accomplished with an Old Delft Hansen processing unit with Kodak E4 chemicals according to standard recommendations. The film in this processing unit is wound onto a spiral which is then moved from tank to tank.

A filter combination-exposure series for selection of the optimum combination was taken at 2,500 m. (See Plate 1.) Exposures were made at one-stop intervals and filters were mounted behind the lens. Plate 2 shows an example of photography from an altitude of 13,000 m.

ACKNOWLEDGEMENTS

The author acknowledges the assistance of Dr. J. H. J. Coetzee in writing the computer program.

LITERATURE CITED

1. Benson, M. L. and Sims, W. G.; Hildebrandt, G. and Kenneweg, H., "The Truth about False Colour Film". *Photogrammetric Record*, 6, 1970, pp. 446-651.
2. Eastman Kodak Company, *Kodak Data for Aerial Photography* M-29, Third Edition, 1971, p. 62.
3. Eastman Kodak Company, *Applied Infrared Photography* M-28, 1968, p. 95.
4. Fritz, N. L., "Optimum Methods for Using Infrared Sensitive Color Films". *Photogrammetric Engineering*, XXXIII, 1967, pp. 1128-1138.
5. Pease, R. W. and Bowden, L. W., "Making Color Infrared Film a More Effective High-Altitude Remote Sensor". *Remote Sensing of Environment*, 1, 1969, pp. 23-30.

PLATE 1. (Upper set of four images on opposite page). *(a) top left.* Kodak 2443 in 114-mm format aerial camera at 2500 m. Filter: 12. Exposure: *f*/8 at 1/200 second. *(b) top right.* Same film and camera as *(a)*. Filter combination: 12 + CC 40M. Exposure: *f*/8 at 1/200 second. Calculated exposure increase relative to *(a)*: 0.20 ≈ ½ stop. *(c) bottom right.* Same camera and film as *(a)*. Filter combination: 12+ 80B. Exposure: *f*/5.6 at 1/200 second. Calculated exposure increase relative to *(a)*: 0.49 ≈ 1½ stop. *(d) bottom left.* Same camera and film as *(a)*. Filter combination: 12 + 80B + CC 40M. Exposure: *f*/2.8 at 1/200 second. Calculated exposure increase relative to *(a)*: 0.68 ≈ 2½ stops.

PLATE 2. Kodak 2443 in 114-mm format aerial camera at 13,000 m. Filter combination: 12 + 80B + CC 40M. Exposure: *f*/2.8 at 1/200 second.