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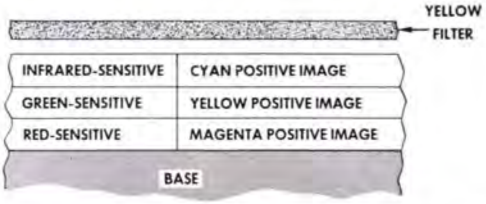

FIG. 1. Arrangement of the layers and filter for Kodak Ektachrome Infrared Aero Film, Type 8443.

Optimum Methods for Using Infrared-Sensitive Color Films

The detection of any condition which affects the growth of plants may be a potential application for the use of this film.

INTRODUCTION

CONSIDERABLE INTEREST has recently been expressed in the use of Kodak Ektachrome Infrared Aero Film, Type 8443, for applications which are as diverse as; military reconnaissance; the detection of disease and insect pests in forests, orchards, and grain crops; the identification of tree species; the study of soil conditions; geological exploration; archeological studies; and medical photography.[1–4] It is thought that a comprehensive description of the film[5,6] and some of its unpublished characteristics, would be useful to many whose field of specialization includes little or no technical photography. Often a knowledge of possible special techniques of use, and a better understanding of the capabilities and limitations of the film, will make the difference between obtaining optimum or unusable results. As this is a false-color film, different interpretive skills are required from those for either black-and-white or normal-color photography. For those potential applications where little concerted work has been done, it is often necessary to determine both the capabilities of the film and the optimum conditions of use for the specific application.

FILM CHARACTERISTICS

Figure 1 shows the arrangement of the principal layers of the film. The bottom layer is sensitive to the red spectral region and, on processing, forms a magenta positive image; the middle layer is green-sensitive and forms a yellow positive image; and the top layer is in-

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* Presented at the Annual Convention of the American Society of Photogrammetry in Washington, D. C., March 1967.

ABSTRACT: *Considerable interest has currently been expressed in the potential of Kodak Ektachrome Infrared Aero Film, Type 8443, as a remote sensor for applications as diverse as aerial reconnaissance and the detection of diseases and pests in agricultural crops. The results obtained with this film can be optimized through a knowledge of some of its special characteristics, and by using photographic techniques which take advantage of its unique properties. Consideration of the typical scene characteristics indicates that the principal applications at the present time involve the photography of foliage. By observing appropriate methods for storing, exposing, and processing, one is assured of obtaining photographs having the highest information content.*

frared-sensitive and forms a cyan positive image. The relationship between the spectral regions of individual-layer sensitivities, and the resulting dyes can be better explained with the aid of Table 1. On the first line, the portion of the electromagnetic spectrum to which photographic materials are sensitive is divided into five regions: the blue, green, and red regions of the visible spectrum, and the ultraviolet and infrared regions at shorter and longer wavelengths, respectively. A normal-color film has three principal layers, one of which is sensitive to blue light, one to green, and one to red (line 2). On processing, positive images of yellow, magenta, and cyan dyes are formed in the respective three layers (line 3).

Withoug going into the chemical and physical reasons of why the film behaves as it does, we know that the resulting images combine to form colors which closely match those of the original subject. That is, blues will be rendered blue, greens green, and so forth (Table 1, line 4). With Ektachrome Infrared Film, one layer is sensitive to green, one to red, and the third to infrared. In addition, however, all three layers are sensitive to the blue region (line 5). To limit the exposure of each layer to only one spectral region, a yellow filter is always used over the camera lens to absorb this blue light before it reaches the film (line 6). The same three dyes are used as in normal color film, and in the same order—yellow, magenta, and cyan—for successively longer wavelength regions (line 7). Again, after processing, the colors blue, green, and red are formed, but the blue has resulted from green exposure, green from red exposure, and red from infrared exposure (line 8).

The relationship between the colors photographed and those resulting in the film can be remembered more easily by noting that the sequence of the reproduced colors is in the same order (blue, green, red) as it is in the spectrum, but the correspondence to the colors being photographed (green, red, and in-

TABLE 1. PRINCIPLES OF OPERATION OF NORMAL COLOR FILM AND OF KODAK EKTACHROME INFRARED AERO FILM, TYPE 8443

1. Spectral region	Ultraviolet	Blue	Green	Red	Infrared
2. Normal color film sensitivities		Blue	Green	Red	
3. Color of dye layers		Yellow	Magenta	Cyan	
4. Resulting color in photograph		Blue	Green	Red	
5. EKTACHROME Infrared sensitivities		Blue	Green	Red	Infrared
6. Sensitivities with yellow filter			Green	Red	Infrared
7. Color of dye layers			Yellow	Magenta	Cyan
8. Resulting color in photograph			Blue	Green	Red

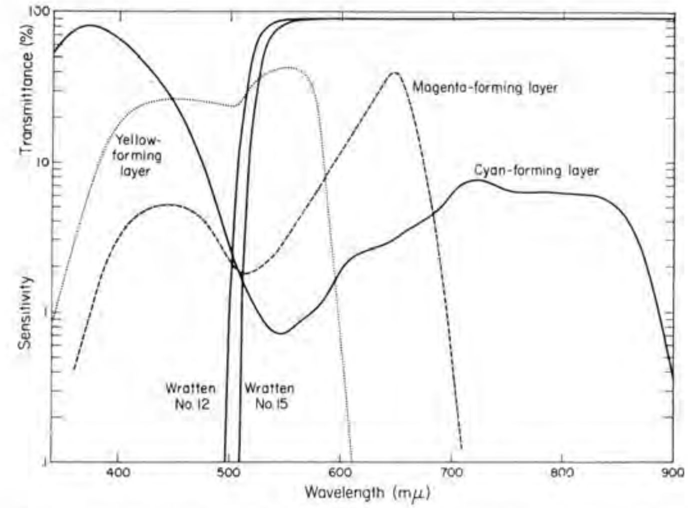

FIG. 2. Spectral sensitivities of the three film layers. Spectral transmittance of Kodak Wratten Filters as indicated.

frared) is one block (Table 1) toward longer wavelengths. With a knowledge of this relationship it is possible to predict readily the reproduction color of any colored object, provided its infrared reflectance is known. Likewise it is possible to predict reproduction color changes with color changes in the objects photographed. For example, if a tree loses infrared reflectance, the reproduction becomes less red or more cyan, which is the characteristic blue-green color of unhealthy trees, as recorded by this film.

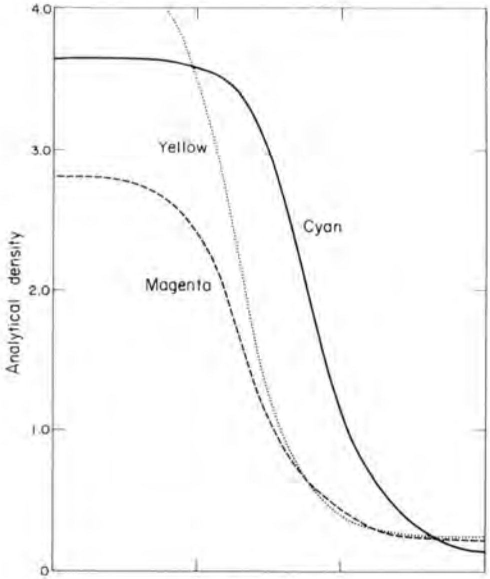

FIG. 3. Sensitometric curves.

So far, the individual layer sensitivities of this film have been presented as broad regions of the spectrum. The actual spectral sensitivities of each layer are given in Figure 2. Plotted on the same graph are the spectral transmittances of Kodak Wratten Filters No. 12 and No. 15. The Wratten Filter No. 15 was recommended for use with the forerunner of this film, Kodak Ektachrome Aero Film (Camouflage Detection). When the present film was developed in 1962, it was decided to use a Wratten Filter No. 12, because most aerial photographers would already have this filter or a similar one for use with black-and-white photography. The basic color balance of the film was then changed to compensate for the change in filter.

The sensitometric curves for the film are shown in Figure 3 and represent what is thought, at the present time, to provide the best color balance for the greatest number of applications. Special applications may require a slightly different balance, which can be obtained by means of filters. Note that, unlike normal color films in which the three layers are all of about the same speed, the cyan layer is considerably slower than the other two. The reason for this is explained later.

SCENE CHARACTERISTICS

The main applications of this film, at the present time, involve the photography of foliage of one form or another. Determining the characteristics of the foliage or plant itself may be the primary object of the photograph, or it may be to reveal the presence of disease or insect pests, or a means of determining soil or subsoil conditions. The detection of any condition which affects the growth of plants may be a potential application for the use of this film. As foliage is often the primary subject photographed, Figure 4 is included to show typical spectral reflectances of a number of types of foliage.[7] It should not be inferred that the types of foliage named always have the properties represented by these curves, because the actual values of reflectance are in many instances greatly affected by such conditions as the age of the leaf, the season, the water and mineral content of the soil, or the type of soil itself, to name just a few. An example of how soil conditions affect the color and growth of foliage is the familiar effect of fertilizer and water on lawn grass in the middle of summer. Most types of foliage are not very different from one another in spectral reflectance in the visible region of the spectrum. As shown in Figure 4, the small rise of each curve in the green region is all that is required to provide the characteristic green appearance. Although differences in foliage color certainly are visible, they are generally small compared to the gamut of greens possible with dyes. However, the generally high reflectance of foliage in the infrared region and the great differences in reflectance which can and do occur, explain the value of a film sensitive in this region for detecting differences in foliage conditions and between varieties of foliage. As these differences are recorded together with those which do occur in the visible region, the color film will provide more information than a black-and-white infrared-sensitive film.

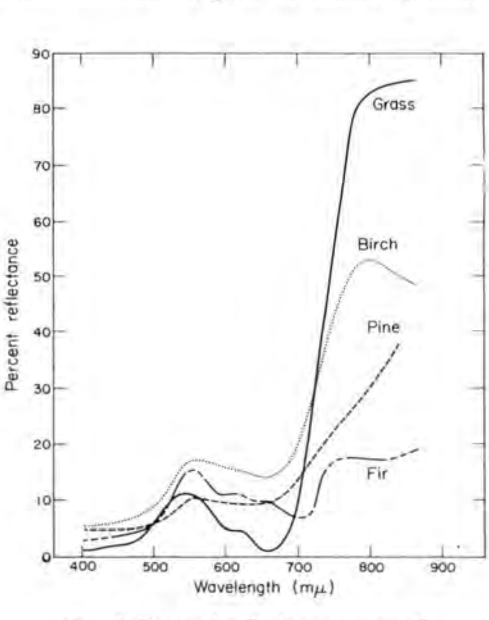

FIG. 4. Spectral reflectance curves of various typical foliage types.

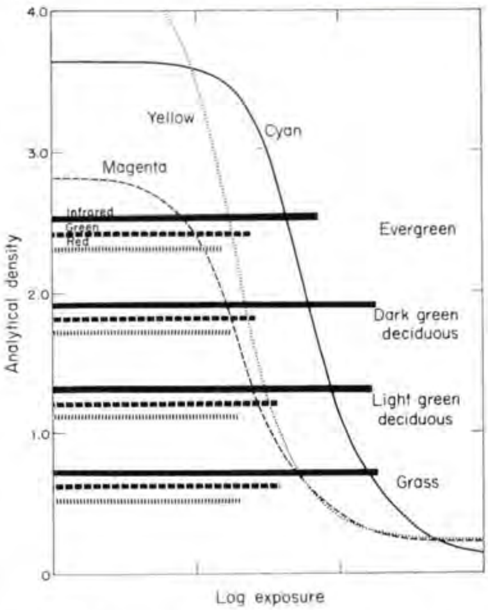

FIG. 5. Bar graph showing the relative exposure produced in each layer of the film by four types of foliage, superimposed at an optimum exposure level on the sensitometric curves.

In order to find the approximate relative exposure produced in each of the layers, measurements have been made of four types of foliage in about 50 aerial photographs. Figure 5 is a bar graph showing the average exposure of each layer of the film by grass, light and dark green deciduous foliage, and evergreens. Note that in all cases the exposure of the cyan layer is considerably greater than that of the other two layers. The grass was recorded almost identically to light green deciduous trees, whereas evergreen trees produced less exposure in all layers and their infrared exposure, relative to the green and red, was less than that for other types of foliage. These facts correspond well with what would be expected from the spectral reflectance curves shown in Figure 4. The exposure bar graphs are superimposed on the sensitometric curves of the film to show the average individual layer densities which result when the foliage is given what is considered to be an optimum exposure.

It can now be seen why the cyan layer has been deliberately made so much slower than the other two layers. If the cyan layer had been as fast as, say, the magenta layer, and the camera exposure was such that the other two layers were exposed as shown in Figure 5, the infrared exposure would be on the toe of cyan curve, and any variation of infrared exposure would produce negligible cyan density change. Thus, all foliage, with the possible exception of evergreens, would be recorded excessively red and small differences in infrared reflectance would not be detectable. With the properly balanced cyan layer, the infrared exposure is recorded well up on the sensitometric curve, and small variations in exposure result in significant differences in cyan density.

For many applications, the usefulness of this film will depend primarily on its ability to record slight changes in infrared reflectance. For example, the first indication of the loss of vigor in a plant due to the incidence of disease or infestation with pests may be a loss of infrared reflectance. This effect often occurs even before any visible symptoms can be detected. Where these conditions are suspected, testing the plants for loss of infrared reflectance, rather than waiting for visible symptoms to appear, will allow countermeasures to be started sooner.

PHOTOGRAPHIC CHARACTERISTICS

Ideally, if one wished to detect photographically the differences or changes in spectral reflectance, it would be desirable to have spectrophotometric curves from which to find the spectral regions of greatest difference. Thus, with suitable filters, photographs could be made in these regions, and the regions where no differences occurred could be eliminated. This method would provide the greatest degree of differentiation. Because suitable spectrophotometric equipment is not available to many people on low budgets, simple techniques eixst which will assure that the best results possible have been attained. Without going to multiband black-and-white photographs which are quite difficult to analyze, we can choose the obvious first technique: to use color photography, which at least divides the spectrum into three discrete bands. If both normal-color and infrared-sensitive color films are used, there are four spectral bands with which to work.

Several characteristics of this film have a bearing on its ability to provide optimum differentiation. Two of them make it possible to obtain good results even on extremely hazy days. The first is the fact that a yellow filter is always used, thus eliminating the blue light, which contributes most to the degrading photographic effect of haze. The second is that the film has a high gamma, as can be seen from the characteristic curves. This high gamma tends to offset what effect there is of haze in the green and red spectral regions.

A consequence of the high gamma is that the film has a rather short exposure latitude. The range for optimum results is only about $\frac{1}{2}$ stop on either side of the best exposure. Beyond that, some decrease in the information will occur, although some compensation can be made by adjustments in the processing if the exposure is known to be not optimum. Thus, for critical applications, or when one is studying the use of the film for a new application, the use of a short exposure series is recommended.

This film has an Aerial Exposure Index of 10 and an ASA rating of 100. Under normal conditions of use, an aerial exposure of about 1/500 second at $f/5.6$ has been found to be quite close to optimum. Thus a typical exposure series would include this value and a half-stop on either side. It is recommended that the camera be focused at the normal setting, rather than at the infrared setting which some cameras have. Two of the film layers, being sensitive in the visible region, require the normal setting. The infrared-sensitive cyan layer is usually well exposed, because of the high infrared reflectance of foliage, and thus its dye concentration is reduced. The effective image, therefore, is predominantly in the magenta and yellow layers.

Experiments have been made with this film for the detection of disease and damage by insects with close-up photography from the ground. These attempts have not always been successful, and some cases are on record where differentiation readily discernible in aerial photographs cannot be detected in photographs made on the ground. The reason for this effect is not entirely understood, but appreciable evidence indicates that at the large scale of a close-up photograph in which individual leaves are seen, considerable variation occurs in the rendition from leaf to leaf because of the high dependence of reflectivity on leaf orientation and on the direction of the light source. This variation is, in many cases, greater than the effect being sought. By increasing the distance from the subject, the variations in the individual leaves are integrated and the average effect can be detected.

Some attempts to record from the ground known abnormal conditions in trees within a forested area have failed because the effective scene luminance range is too great.

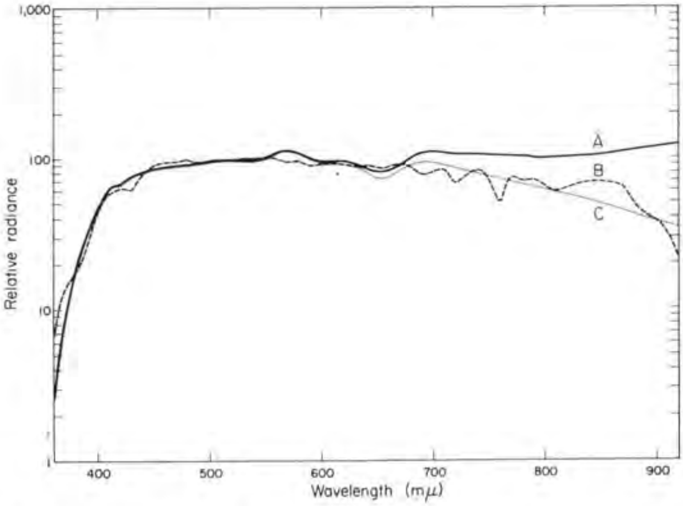

FIG. 6. The spectral distribution of daylight *B*, of a sensitometric source suitable for films sensitive in the visible region *A*, and of the same source with the addition of a partial infrared-absorber *C*.

This large range is due not only to the normal differences in illumination between sunlit areas and shade, but also to the fact that shaded areas are illuminated by skylight, which is largely eliminated by the yellow filter. As mentioned before, the exposure latitude of the film is short and photographs which include both sunlit foliage and shaded areas under trees will not record both well. As the shaded areas often predominate, there is a tendency to overexpose, with the resultant loss of differentiation in the sunlit foliage. In these photographs, all such areas tend toward a white reproduction and the changes from red or magenta toward yellow and green cannot be obtained.

Several experimenters have attempted to study aquatic vegetation with this film. Knowing that infrared radiation is highly absorbed by water, we made a study to determine accurately the spectral absorption of pure water as recorded by the three layers of this film. One foot of water was found to have the effect of a density of 0.04 in reducing the exposure for the green-sensitive layer, 0.06 for the red-sensitive layer, and 0.22 for the infrared-sensitive layer. By including the surface reflectance of the water, and considering that the light must pass through the water twice, it can be calculated that a one-foot depth of water will decrease the exposure of the green- and red-sensitive layers by about $\frac{1}{2}$ stop and that of the infrared-sensitive layer by about $1\frac{1}{2}$ stops. This film is not useful therefore for photography through any great depths of water.

There is a tendency to equate infrared radiation with heat, and to expect that this film can be used to record temperature differences. Tests have shown that, if no other source of radiation is present to affect the film, an object heated to 650°F will just be recorded by the infrared-sensitive layer of the film where the film is exposed for 15 minutes at $f/2.0$. The film will not record temperature differences at our environmental temperatures.

If exposures are made when the film is very cold, some loss in speed occurs, as well as a shift of color balance in the cyan direction. For normal low-altitude work, these effects are not significant, but for photography at high altitudes, with unheated or partially heated cameras, marked changes may result. As an example, a sensitometric test showed that where the exposures were made with the film at −40°F, the speeds of the green- and red-sensitive layers were decreased by 0.20 in log E, and that of the infrared-sensitive layer was decreased by 0.60.

In exposing the film on a sensitometer, it is necessary to consider the spectral energy distribution of the light source in the infrared region. A commonly used daylight sensitometric source is composed of a tungsten-filament lamp with a suitable Corning 5900 glass filter. Although this source provides a satisfactory match for daylight in the visible region, the radiation in the infrared region is relatively too great. Figure 6 shows the current best estimate of the spectral distribution of daylight[8,9] at the camera film plane, the distribution of the filtered tungsten source described, and the improvement in the infrared region which can be attained by the addition to the filter of 1.0 mm. of Pittsburgh 2043 glass. This lamp—filter combination provides a daylight source which is suitable for films which are sensitive either in the visible or the near-infrared regions of the spectrum.

PROCESSING

This film was designed to be processed in Kodak Ektachrome Film Process E-2 and E-3, and if fresh film is processed according to instructions, it will have the sensitometric characteristics shown in Figure 3. It is recommended that the user process his own film, but if this is impracticable, assurance should be obtained from the processor that Process E-2 and E-3 will be used, and that no infrared inspection will be made during processing. For critical applications, E-4 processing is not recommended. This process increases the speed of the cyan layer by about 0.20 in log E, causing the photographs to be more red than is desirable for optimum rendition.

If faster film is desired, or if a roll is known to be underexposed, an increase in speed can be produced by a change in processing. The speed can be increased by about one stop by increasing the first developer time by $4\frac{1}{2}$ minutes. Sensitometric tests of this modified process indicate some decrease in the shoulder densities and a slight change in color balance. It is thought though, that these changes are preferable to obtaining results which are more than a half-stop underexposed.

In the Kodak Ektachrome RT Processor, Model 1411-M, the EA-4 process for Ektachrome films increases the speed of the cyan layer by about 0.20 in log E. However, a process modification is available will produce optimum results. It consists of an addition to the prehardener, and a change in the temperature of the first developer.

At present, no process exists which will produce a good color negative with this film. If it is processed in the Kodak Color Film Process C-22, the contrast of the cyan layer is very low. Prints from these negatives show not only poor color rendition but also a major loss of differentiation between foliage types having different infrared reflectances.

COLOR BALANCE

One of the characteristics of this film which must be understood in order to obtain consistently optimum results is the effect of age on its color balance. The infrared-sensitive cyan layer tends to decrease in speed as the film ages, and the speed of the green-sensitive yellow layer increases slightly. As the film ages, its color balance shifts toward cyan. If the film is kept at room temperature, its balance will eventually pass the point of optimum color discrimination. However, this effect can be reduced considerably by refrigeration, or almost eliminated by storage in a freezer.

As a time lag always occurs between when the film is manufactured and when it is marketed, it is coated with the cyan layer slightly fast. By the time the film reaches a customer, the speed of this layer will usually have slowed sufficiently so that the color balance is normal. Because the color of reproduction is important in the use of this product, it is sometimes desirable, for optimum results, first to determine the actual color balance of the film and then to make adjustments by means of filters.

Several tests have indicated that the ability of this film to discriminate between varieties of trees and between sick and healthy trees, depends both on the exposure and on the color balance of the photograph.[3] Careful attention to these factors will assist greatly in determining the film's usefulness for particular applications. The color balance of normal color films is readily changed in any direction with gelatin Kodak Color Compensating (CC) Filters. Figure 7 shows the spectral transmittance of some typical CC filters superimposed on the spectral sensitivity curves of the film. As can be seen, not one of these filters absorbs in the infrared region. Thus, with no effective absorber for the infrared-sensitive cyan layer, it is impossible to obtain the entire gamut of colors with the convenient gelatin filters alone. The Corning 3966 glass filter does absorb infrared (Figure 7), and suitable thicknesses can be made to obtain any desired decrease in the speed of the cyan layer. This filter is thus useful both for experimenting with color balance, and for slowing the cyan layer of film having an overly red balance. Tests have shown that a standard thickness of this filter will change the color balance by about $\frac{1}{2}$ stop in the cyan direction. Seldom is more than half this thickness needed.

To determine the optimum color balance of the film to provide maximum detectability for particular applications, it has been found desirable to make a series of photographs in which both the exposure and the color balance are varied systematically. Figure 8 is a convenient trilinear plot showing the results of a sensitometric test made to determine the

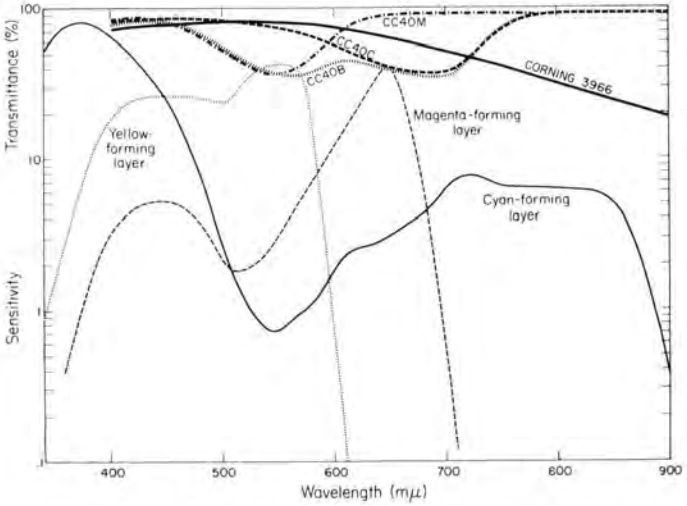

FIG. 7. Transmittances of typical Kodak Color Compensating Filters superimposed on the spectral sensitivity curves.

effect of various filters on the color balance. The *0* point is the balance of the particular coating used, and the direction and distance from *0* indicate the color and magnitude of the shift produced by the filter or combination of filters shown. The CC-magenta filters shift the balance in the yellow direction, the CC-blue filters in the red direction, and the Corning 3966 toward the cyan. The balance can be shifted in the magenta direction with CC-cyan filters, or in the blue direction with combinations of CC-cyan and Corning 3966 filters, but these are seldom necessary. The CC-red filters produce the same results as the CC-magenta because the difference between them is primarily in their blue absorption, and this spectral region is eliminated with the Wratten Filter No. 12. For the same reason, the CC-green and CC-cyan filters produce similar results.

If, now, for a particular application, an exposure series is made at the color balance of each of the points shown in Figure 8, one will obtain an array of various colored photographs which can be studied to find optimum discrimination. Such arrays have been made to determine the optimum color balance to distinguish between varieties of deciduous trees in a northern forest area, and to indicate decline and disease in citrus trees in Florida.

In Figure 9 the results of these investigations are plotted and show the color-balance regions of maximum discrimination encompassed within the area of the inner black lines, some discrimination still being apparent out to the outer lines. The data for the second part of the figure are the same as those for Figure 1 in Reference 3, except that they are presented here in terms of analytical rather than integral densitometry, and an adjustment has been made because the original color balance of the film was different in the two tests. As

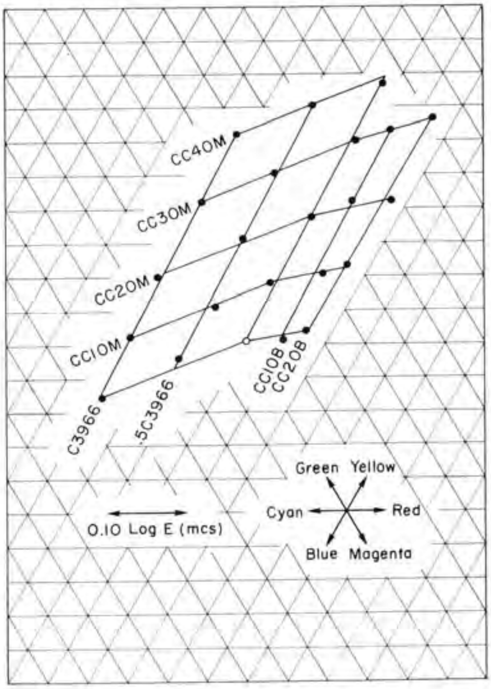

FIG. 8. Color shifts produced by various combinations of Kodak Color Compensating and Corning No. 3966 filters.

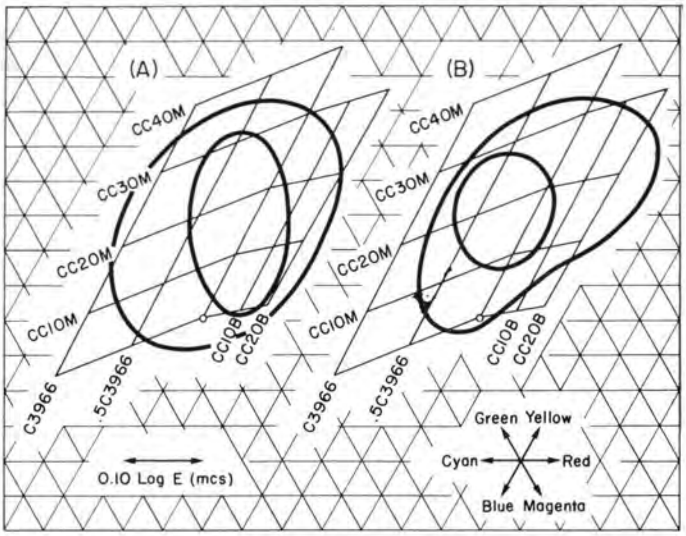

FIG. 9. Color-balance regions for maximum discrimination in *A* northern forest areas, and *B* Florida citrus trees.

can be seen, the optimum balance depends somewhat on the subject matter and, in general, lies within a rather small region. This illustrates that for those seriously interested in developing techniques for using this film for particular applications, the generation of such an array can be quite helpful. The results of these tests indicate that a rather purplish reproduction is preferable to the more esthetically pleasing red preferred by some people. This conclusion has also been reached by others who have compared results obtained with fresh and somewhat older films.

FIG. 10. Paired camera arrangement for making simultaneous photographs.

To obtain the most consistent results, all photographs should be made of the same area from about the same point, which, unless a helicopter is used, requires quite a bit of flying around. It may also be found desirable to evaluate the effects of such variables as the plane altitude, the solar altitude, the angle between the direction of the sun's rays and that of the camera, etc.

An exposure series of three photographs spaced at half-stop intervals is usually sufficient, so a complete color-balance—exposure-series array will consist of 69 photographs. A convenient arrangement is to use two identical 35 mm cameras mounted on a pair of handles (Figure 10) so that both shutters can be tripped at once. By rapidly operating the film-advancing and aperture-setting mechanisms, it is possible from 8,000 feet to make one exposure series on each camera on each pass past the target, and filters can be changed while the plane is going around for the next pass.

Because all filters have some absorption in their regions of highest spectral transmittance, and because the three layers of a color film have somewhat overlapping sensitivities, the effect of adding filters is not only to

TABLE 2. EXPOSURES REQUIRED FOR VARIOUS FILTER COMBINATIONS

Filter Combinations	*Aperture (for 1/500 sec. expos. time)*		
Wr. No. 12[a]	*f*/4.7	5.6	6.7
Wr. No. 12+CC10M[b]	*f*/4.7	5.6	6.7
Wr. No. 12+CC20M	*f*/4.7	5.6	6.7
Wr. No. 12+CC30M	*f*/4.7	5.6	6.7
Wr. No. 12+CC40M	*f*/4.0	4.7	5.6
Wr. No. 12+CC10B	*f*/4.0	4.7	5.6
Wr. No. 12+CC10B+CC10M	*f*/4.0	4.7	5.6
Wr. No. 12+CC10B+CC20M	*f*/4.0	4.7	5.6
Wr. No. 12+CC10B+CC30M	*f*/4.0	4.7	5.6
Wr. No. 12+CC20B	*f*/4.0	4.7	5.6
Wr. No. 12+CC20B+CC10M	*f*/4.0	4.7	5.6
Wr. No. 12+CC20B+CC20M	*f*/4.0	4.7	5.6
Wr. No. 12+CC20B+CC30M	*f*/4.0	4.7	5.6
Wr. No. 12+1/2C3966[c]	*f*/4.0	4.7	5.6
Wr. No. 12+1/2C3966+CC10M	*f*/4.0	4.7	5.6
Wr. No. 12+1/2C3966+CC20M	*f*/4.0	4.7	5.6
Wr. No. 12+1/2C3966+CC30M	*f*/4.0	4.7	5.6
Wr. No. 12+1/2C3966+CC40M	*f*/3.4	4.0	4.7
Wr. No. 12+C3966	*f*/3.4	4.0	4.7
Wr. No. 12+C3966+CC10M	*f*/3.4	4.0	4.7
Wr. No. 12+C3966+CC20M	*f*/3.4	4.0	4.7
Wr. No. 12+C3966+CC30M	*f*/3.4	4.0	4.7
Wr. No. 12+C3966+CC40M	*f*/2.8	3.4	4.0

[a] Kodak Wratten Filter Number.
[b] Kodak Color Compensating Filter.
[c] Corning Filter Number.

change the color balance, but also to decrease the exposure. Table 2 shows the complete set of filter combinations and exposures required to produce the above array on a clear day if the solar altitude is above 40 degrees.

SHARP-CUTTING FILTERS

Considerable experimental work has been done to determine the effect of using various sharp-cutting filters, including band pass, band rejection, and high pass at longer wavelengths than that of the Wratten Filter No. 12. These filters have included the high-pass Wratten Filters No. 22, 25, and 70, and the band-rejection filters Wratten No. 55, Corning 9830, and a special dichroic one which cuts out the near-infrared sensitivity of the cyan layer. Combinations of these filters are essentially band-pass filters for isolating individual spectral regions. The effect of all these filters has been to change the color balance from optimum, with the resultant loss in discriminating ability. It has also confirmed what has been known for pictorial color photography for some time, namely, that one- and two-color photographs do not provide as much information as do three-color photographs.

The effect of using high-pass filters of shorter wavelength cutoff than that of the Wratten Filter No. 12 has not been tested adequately. These filters include the Wratten Nos. 8, 3, 2E, and 2C. When these filters are used, the color balance can be brought back to optimum with the color-balance-adjusting filters described. As all three layers are sensitive in the blue region, some increase in speed should be obtained, but it is believed that the desaturation caused by exposing all three layers with blue light will decrease the sensitivity of discrimination.

CONCLUSIONS

From the facts presented, it can be seen that, like all advances in the state of the art, improved results do not necessarily come easily. It is considered that with a better understanding of the characteristics of the film, and a willingness to perform some experimentation, the effectiveness of this film for various remote sensing applications can be demonstrated. The experiments conducted to date indicate considerable promise of useful results, along with savings in cost over present ground-based methods.

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