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New Color Film for Water-Photography Penetration

An experimental film is superior to both a regular color film and to a film made by omitting the blue-sensitive layer.

INTRODUCTION

SINCE oceanographers have had the opportunity to study some of the Gemini and Apollo mission photographs of the oceans and coastal regions of the world, a great deal of interest has been generated in the potential of photographic remote sensing for revealing features of the underwater environment. In addition to the use of aerial photography in the important task of mapping coastal areas, photography from the air can reveal significant oceanographic data about currents and tides, the presence of obstructions, shoals and reefs, water depths, marine life, biological composition, and characteristics of bottom materials.

To provide maximum information about subsurface features in water bodies, it is important that the camera, film and photographic techniques be optimized to provide the greatest penetration of the water and maximum discrimination between the elements of interest and their background. In view of this need, an experimental color aerial film was made based on the best data available on the characteristics of water bodies and color photography. Practical tests were than made to test its usefulness for oceanographic and hydrographic applications.

This paper describes the theoretical basis for the design of the film, its photographic characteristics and the results obtained with it in aerial photographic tests.

ABSTRACT: *The need for a film which will provide maximum information about underwater detail and water characteristics from photographs made from the air has led to the design of a special film for this purpose. A study of the transmittance characteristics of water shows that a film with two layers having peak sensitivities at about 480 and 550 nm will provide maximum penetration of water with various amounts of organic matter present. It will also allow some estimate of the amount of such material. Maximum detectability in the processed film is accomplished by providing that the dyes formed in the two layers are the complementary colors magenta and green, and that the contrast of the film be high. Aerial photographs made with an experimental film designed with the above characteristics show its superiority over regular color film for delineating underwater detail, and the distinct superiority of both over a film made by omitting the blue-sensitive layer from a regular color film.*

TRANSMITTANCE CHARACTERISTICS OF WATER

In designing a film for a specific application, it is important to consider the characteristics of the scene to be photographed, the illuminant, and the media through which the light travels from the source to the scene and back to the camera. In oceanographic applications where one is interested in optimizing the aerial photographic system to provide imagery of subsurface detail, special consideration must be given to the transmittance and attenuation properties of the water. Although the characteristics of the air path are also important, particularly in high-

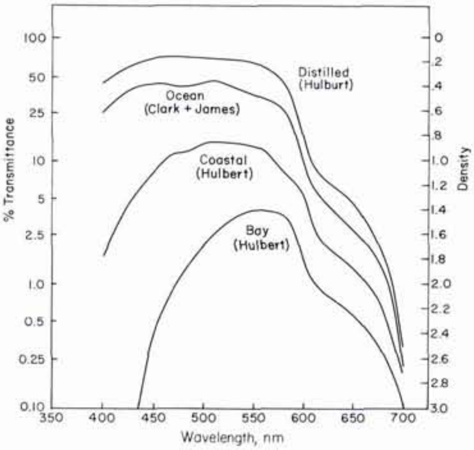


FIG. 1. Spectral transmittance for ten meters of various water types.

altitude aerial photography, these are better understood and provide less constraint on the design of an optimum system than do those of the water medium.

The transmittance of water has been measured by a number of investigators. Representative of the data are those derived by Hulburt in 1945.[1] His curves are shown in Figure 1 and represent the spectral transmittances of light through ten meters of distilled water, coastal Gulf Stream water, and Chesapeake Bay water. The data are presented in terms of both transmittance and density (one scale on each side of the Figure) rather than in the more commonly used form of attenuation constant or its reciprocal, the attenuation length. We have chosen to show the data in this fashion because photographic scientists are more familiar with these units and they provide, in our opinion, data in a more useful form. The relationship among transmittance, density, and the attenuation coefficient is easily derived.*

Clarke and James[2] have also measured the transmittance properties of distilled water. Their data are not significantly different from those of Hulburt. The transmittance properties of clear ocean water are similar to those of distilled water as has been noted by Clarke and James,[2] Jerlov,[3,4] and Lankes.[5] Although the absolute level of transmittance of different types of ocean water varies, the shapes of the curves are similar, with only slight differences in the wavelengths at which the peak transmittances occur. Data provided by Clarke and James for unfiltered ocean water, which they have identified as continental slope water, illustrate this point and are shown in Figure 1 as well.

It is apparent from the Figure that the maximum transmittance of light in distilled and clear ocean water occurs in the spectral range between 440 and 540 nm. In this regard, Duntley[6] notes that "Water possesses only a single important window, the peak of which lies near 480 nm unless it is shifted toward the green by discolored yellow substances. . . . Clear ocean water is so selective in its absorption that only a comparatively narrow band of blue-green light penetrates deeply into the sea. . . ."

In coastal and bay waters, the peak transmittance of light shifts toward longer wavelengths. This shift is a result of the presence of the *yellow substances* referred to by Duntley and is generally attributed to dissolved organic materials and plankton. In addition to a shift in the spectral transmittance peak, there is also a significant decrease in total transmittance. Hulburt's data show a decrease in transmittance at the peak wavelengths of a factor of about 16 times between distilled water and bay water. The significant point, however, is that the maximum transmittance for fairly turbid waters, as typified by Hulburt's bay water curve, occurs at a wavelength of about 550 nm.

SPECTRAL REFLECTANCE AND IRRADIANCE

The spectral transmittance of water is just one of the elements to be considered in the design of a film for water penetration. Two other important parameters are the spectral reflectance of the objects themselves and the spectral irradiance falling on the scene.

It is rather difficult to typify the color and, more particularly, the spectral reflectances of the objects that one might be interested in photographing, for they undoubtedly range throughout the spectrum. Depending on the application, one might be interested in photographing scene elements, such as bottom sand, reefs, marine life, underwater vegetation, and obstructions. The colors of these objects are so dissimilar that it is pointless to try to approximate them by a typical reflectance curve. This is not to say that the color

* The attenuation coefficient α is defined in the equation $i = i_0 e^{-\alpha x}$, where i and i_0 are the intensities of a parallel (unscattered) beam of light with a wavelength λ, which enters and emerges respectively from a thickness x cm of water. Transmittance is defined as $T = i/i_0$ and density as $D = \log_{10}(1/T) = \log_{10}(i_0 i)$. The relationship between density and the attenuation coefficient is therefore $D = .4343\alpha x$ where x, again, is the thickness of the water path in cm.

of an underwater object is not an important consideration in determining whether one can obtain a satisfactory photographic image of it, but rather that not a great deal can be learned about the required photographic film sensitivities from a consideration of the possible targets.

The spectral irradiance of daylight beneath the surface of natural water bodies is, however, an important consideration in the design of a film for oceanography, because it provides us with information about the color of the radiation illuminating the scene elements. It might seem reasonable to determine the spectral irradiance underwater by multiplying, wavelength by wavelength, the spectral irradiance from the sun and sky at the surface by the spectral transmittance of water. This procedure is difficult, however, and full of pitfalls; the distribution of light underwater is a function of several variables, such as solar altitude, depth, sea-state (water-surface conditions), and the scattering and absorption characteristics of the water, and is quite different from that which exists above the surface.

Fortunately, several investigators have recently made measurements of this downwelling spectral irradiance. Tyler and Smith[7] have gathered data at a number of locations and at various depths of both downwelling and upwelling irradiance. Included in their comprehensive work was a study of the irradiance in Crater Lake, Oregon, which is generally regarded as being extremely pure. Tyler and Smith point out that as a result of its purity, measurements in this lake define the upper limit of the penetration of daylight energy into water. Calculated values of spectral irradiance indicate that at extreme depths (600 meters) the maximum downwelling irradiance occurs at a wavelength of about 415 nm. At a depth of 25 meters, their data show the peak transmission occurring at approximately 450 nm but, as would be expected, the curve has a broader and flatter peak than at the greater depths.

Although it is not possible to characterize in a few statements the extensive measurements obtained by Tyler and Smith, a review of their data obtained in both ocean and gulf waters shows that the maxima of the spectral downwelling irradiance curves occur generally in the 400- to 550-nm range with very rapid attenuation at longer wavelengths. Their data for San Vincente, which they characterize as a man-made lake heavily contaminated with phytoplankton, zooplankton, and plankton decomposition products, show that peak irradiance occurs between 550 and 570 nm at depths between one and ten meters.

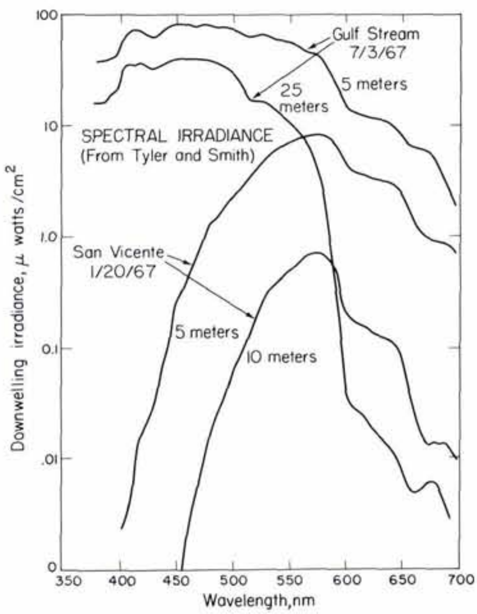


FIG. 2. Downwelling spectral irradiance measured by Tyler and Smith.

This is demonstrated in Figure 2, which presents some of the data obtained by Tyler and Smith. Curves representing measurements, corrected for sun angle changes, made at two depths at both San Vincente and the Gulf Stream are shown. The shift that occurs in the wavelength of peak irradiance and the differences in total irradiance at these two locations are dramatic evidence of the differences between clear ocean and heavily contaminated waters.

Another study of downwelling spectral irradiance was made by Ross *et al.* using the Ben Franklin submersible.[8] Using a spectroradiometer mounted to look upward through a port in the submersible, downwelling spectral irradiance data were collected in the Gulf Stream at depths down to 45 meters. The data obtained during this experiment are reproduced in Figure 3, and are generally consistent with those reported by Jerlov,[3] with regard to the shape of the curves and the wavelength of peak irradiance. However, the authors note that the peak energy level is somewhat lower. The conclusion is reached that the maximum energy measured by the instrument occurs at a wavelength of about 475 nm and that the ratio of blue to green light increases as the depth increases.

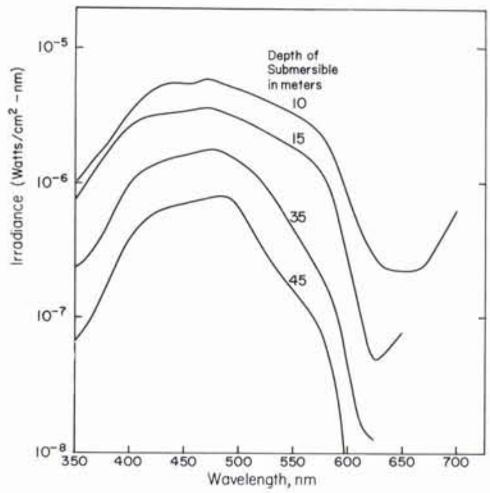


FIG. 3. Downwelling spectral irradiance measured in Ben Franklin experiment.

From a study of the spectral irradiance data reported by these investigators, it is apparent that light reaching the underwater scene is largely confined to the blue and green spectral regions. This conclusion has been validated in several aerial photographic studies which are discussed below.

Aerial Photographic Studies of Water Penetration

Concurrent with the measurements of downwelling irradiance made from the Ben Franklin submersible, aerial photographic tests were conducted by the study group. Aerial photographs of the deck of the submersible, which was painted with a matte white paint providing a target area of 13×28 feet, were made using a R4-B, four-lens, multispectral camera. The camera was loaded with KODAK 2484 Pan Film (ESTAR-AH Base), and spectral bands in the blue, blue-green, green, and red were isolated through use of KODAK WRATTEN Filters, Nos. 47B, a $(2E + 38)$ combination, 58, and 25, respectively. Images of the deck were obtained while the submersible was at depths of 10, 15, and 25 meters.

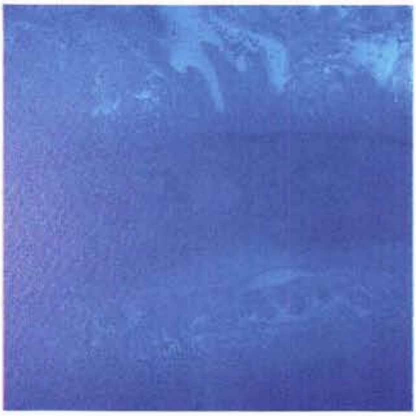
Interpretation of the images included a determination of the densities of the submersible's white deck as it was recorded in each of the spectral bands at various depths. A normalization procedure was utilized to compensate for differences in gamma, exposure, and spectral response and to provide a direct comparison among the four spectral bands, to indicate for each its effectiveness in water penetration. The results, which have been published by Ross,[8,9] indicate that the blue and blue-green spectral bands provided better water penetration than did the green band, and the green was significantly better than the red band. Ross notes that "The failure of the red band to penetrate to ten meters depth is normal, as the absorption factor of water for light in this spectral region is four to five times greater than in the blue and green. Because of the high attenuation factor, the contrast of detail in shallow water appears higher in the red than in the green; however, the same information can be recorded at the same depths in either the blue or green bands, and there is no special virtue in having a red record for penetration, *per se*."

A second study of the penetration of water through use of multispectral aerial photographic imagery has been documented by Helgeson.[10] Using an Itek nine-lens camera and filters to isolate nine separate spectral regions, images were obtained of the Bahama Banks from an altitude of 14,850 feet. Various simulations of bicolor and tricolor photography were made by using images from the different spectral regions. Results of this study indicate that maximum bottom information was recorded when a bicolor display composed of the images from the two bands, 430 to 530 nm and 540 to 620 nm, was used.

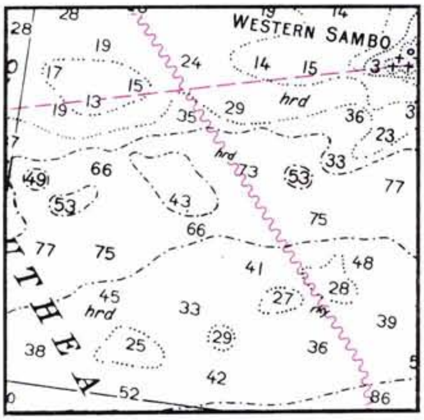
Helgeson and Ross have summarized the results of their research in a co-authored paper.[11] The authors note that some aerial photographic experiments have been made with a color film which has no blue-sensitive layer. The rationale behind the use of this film has been the assumed need to reject the atmospheric haze light, which is predominantly blue, and the blue light scattered in the water. Helgeson and Ross point out, however, that without blue sensitivity, no information is recorded in the spectral region where maximum clear-seawater penetration is possible. In addition, blue-color information is important in revealing biological content because, as the data in Figure 1 imply, the ratio between the amount of blue and green light is a measure of the *yellow substance* content of the water. In summarizing their studies, the authors conclude that "an oceanographic image in the blue region with a blue passband approximately 0.46 to 0.50 μm contains essential information, and atmospheric haze does not negate its value. A green record in the spectral zone 0.50 to 0.58 μm is necessary in conjunction with the blue for quantizing water-color data."

(a)

(b)



(c)



(d)

Plate 1.

Photographs of an area south of Key West, Florida made with (a) the experimental film, (b) a regular color film, and (c) a film made by leaving the blue-sensitive layer off a regular color film, along with (d) the nautical chart of the same area.

A study of northern coastal water penetration using a multispectral camera has been published by Yost and Wenderoth.[12] Using a black-and-white film and a four-lens camera fitted with appropriate broad-band color filters, simultaneous photographs of two identical target arrays were made from an altitude of 1,000 feet. Each target array was made up of six gray panels and a red, green, blue, and yellow target. During the test, one target was submerged to depths down to 30 feet whereas the other was retained on the surface.

The red, green, and blue filters used in the experiment defined spectral regions approximately between 400 and 500 nm, 500 and 580 nm, and 590 and 700 nm. Evaluation of the images led to the conclusion that the green spectral band had greater water-penetration capability than the blue band. These data indicate the importance of the green spectral region for penetration of coastal waters which contain large amounts of particulate matter and *yellow substance*.

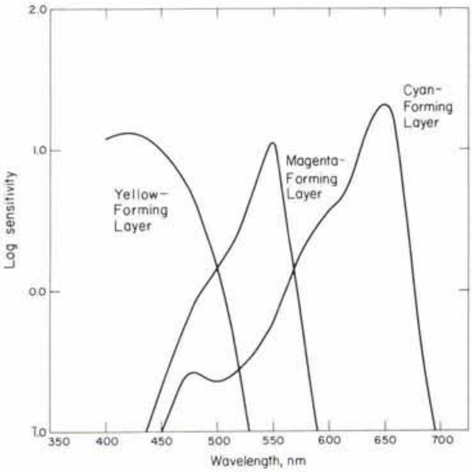


FIG. 4. Spectral sensitivities of KODAK EKTACHROME MS AEROGRAPHIC Film 2448 (ESTAR Base).

DESIGN OF THE FILM

Evaluation of the experimental studies and the available data typifying the transmittance characteristics of water, which have been cited above, led us to the conclusion that a color film designed for oceanographic applications should have sensitivity in both the blue and green spectral regions with no red sensitivity. For penetrating relatively clear ocean and coastal water, a blue-green-sensitive layer peaked in the region of maximum water transmittance, i.e., at about 480 nm, is required. Consideration of (1) the shift in peak water transmittance from blue-green to green in bay and other turbid waters and (2) the need in several applications for a measure of the blue-green-to-green ratio of reflected light indicates that the peak sensitivity to green light should be at about 550 nm. Referring to Figure 1, it can be seen that a color film with two layers sensitized individually at 480 and 550 nm will provide maximum penetration for both ocean and bay waters. In ocean water the blue-green-sensitive layer will provide the deepest water penetration; whereas in bay water, this will be obtained in the green-sensitive layer.

One might wonder whether the blue- and green-sensitive layers of a regular color film would meet these requirements. Figure 4 presents typical spectral sensitivity curves for KODAK EKTACHROME MS AEROGRAPHIC Film 2448 (ESTAR Base). Although the green-sensitive layer is peaked at about the desired wavelength in the green spectral region, the blue-sensitive layer has a peak sensitivity at 420 nm. The wavelength of maximum clear-water transmittance, i.e. 480 nm, falls *between* the peak sensitivities of these two layers. To meet the requirements for water penetration better, the experimental film incorporates the desired sensitivity peak at this wavelength.

The new film has been made with sensitivities to two rather than three spectral regions. The rationale for this design is based on two facts. First, because there is significant attenuation of red light in water, there is no need to incorporate a red-sensitive layer in a film designed for penetration of water. Helgeson and Ross demonstrated that a red-sensitive layer provides information chiefly about surface objects and the sea state. Indeed, our study has indicated that a red-sensitive layer sometimes obscures underwater detail, because images of the surface detail, particularly specular reflections, tend to mask below-surface information. This is because the ratio of light reflected from the surface to that reflected from underwater objects is greater in the red spectral region than in either the blue or green bands.

The second reason for providing a film with only blue-green and green sensitivities follows from the requirement that a film for oceanography should be able to distinguish between the colors of predominantly blue-green and predominantly green waters (e.g., ocean and bay or estuary). It is imperative that maximum color discrimination between these two be provided. The recording of the color differences is achieved through the choice of the spectral sensitivities built into the two layers. The visual display of this information, however, is a function of the dyes formed in the two layers. As maximum visual discrimination of color differences is obtained about the point of color neutrality, it is required that the two film dyes be complementary in color. A film with sensitivity to a third spectral region outside the blue-green range would negate this requirement, because the color of the dye associated with this third spectral region would prevent the possibility of obtaining a neutral with just the blue and green records.

The choice of dyes to be used in the film was made from a consideration of the three principal sets of two dyes which can produce complementary colors, and which are readily available to the film manufacturer—the cyan, magenta, and yellow dyes, and their complements, red, green and blue. In consultation with Dr. D. L. MacAdam of the Kodak Research Laboratories, we decided that the best choice of dyes would be magenta and its complement, green, as the use of these two would provide maximum visual discrimination of color differences. This decision is supported by Dr. MacAdam's recent work with the geodesic chromaticity diagram.[13]

It was decided to form the magenta dye in the blue-green-sensitive layer of the film and the green dye in the green-sensitive layer. The reason for this choice was the desire to make the image formed in the blue-green-sensitive layer, which provides the deepest penetration in ocean water, the one that produces the greatest visual acuity. The eye responds with maximum acuity to green light, which is modulated by the magenta layer.

The decision to make the new film a reversal product giving a positive image was based on the requirement for high contrast to maximize the low-contrast color differences found in the underwater scene, and on the facility that a reversal film provides for direct interpretation. Although a color negative film is desirable if multiple prints are required, this feature seemed less important.

Most current color aerial films are designed to produce optimum characteristics if processed in the new machine processors. The standard process for reversal films in these machines is Process EA-5, and the new film has therefore been designed for this process.

Physical and Photographic Characteristics

The arrangement of the principal layers of the film is shown in Figure 5. The bottom layer is sensitive to the green spectral region, and upon processing, forms the green positive image. As this layer also possesses the inherent blue sensitivity characteristic of most photographic materials, a yellow filter layer is placed over it to prevent exposure by blue radiation. The top layer is sensitive to the blue and blue-green spectral region and forms the magenta positive image. The film is coated on an acetate base with antihalation protection.

The spectral sensitivity curves are shown in Figure 6. In calculating the sensitivities of the green-sensitive layer, it is possible to measure the densities of the green dye in both the red and blue spectral regions be-

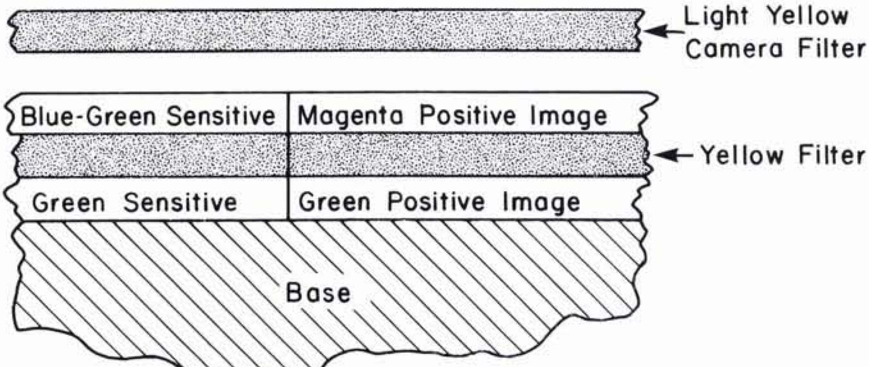


FIG. 5. Arrangement of the layers and filters for the experimental film.

cause it absorbs both red and blue light. Both have been used to calculate the sensitivities, and result in the two curves labeled *R* and *B* in Figure 6.

It can be seen from the spectral sensitivity curves that because the magenta-forming layer has both higher sensitivity and a broader sensitivity range, it is considerably faster than the green-forming layer. This relationship between sensitivities has been made deliberately in order that the spectral sensitivity range can be narrowed with filters to the required blue-green region postulated in the description of necessary characteristics. It also allows control of the speed relationship between the two layers, using the same filters, to provide optimum color balance. Shown also in Figure 6 are the spectral transmittance characteristics of a series of short-wavelength-cutoff filters which have been used in practical tests to accomplish the above objectives. It was generally found that the KODAK WRATTEN Filter, No. 3, provided optimum color balance, and from the curves it can be seen that this filter, in conjunction with the layer sensitivity, provides a sensitivity range comparable to that of the green-forming layer.

Spectral density curves of the two film dyes are shown in Figure 7. These curves represent measurements made on one sample of film and are given to show only the general characteristics of each of the dyes. The relationship between the densities formed will depend on the relative exposure between the two layers, and there may be some differences in the ratio between the red and blue densities of the green dye. As was mentioned previously, the green dye absorbs in both the red and blue regions and measurements made in either will indicate the response of this layer. However, measurement in the red region is preferable because the magenta dye has less absorption there.

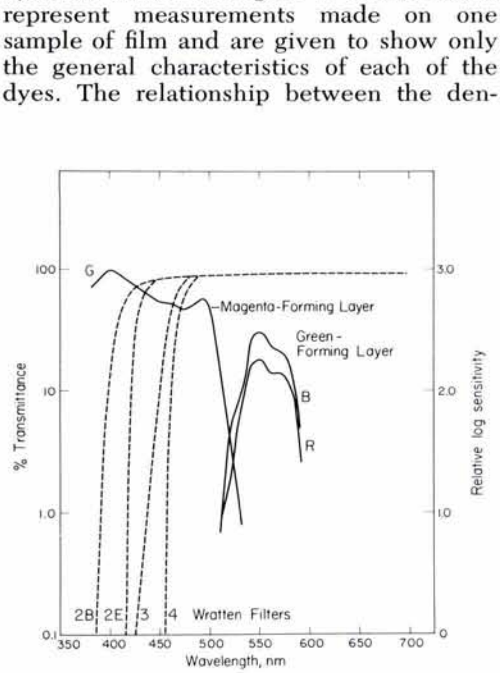


FIG. 6. Spectral sensitivities of the two film layers of the experimental film. Spectral transmittance of KODAK WRATTEN Filters as indicated.

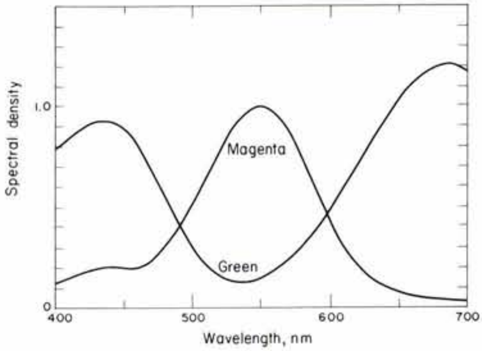


FIG. 7. Spectral densities of the green and magenta dyes formed in the processed film.

Figure 8 shows the sensitometric characteristics of the film when exposed through a WRATTEN Filter No. 3 and processed in a KODAK EKTACHROME RT Processor utilizing Process EA-5 chemicals. Again, it can be seen that both red- and blue-density readings have been made of the green dye. The green curve results primarily from the magenta dye. It should be noted that these are integral density curves, the densities being measured through red, green and blue filters. Integral, rather than analytical, densites are given because they are more representative of what most organizations are capable of measuring, and because an analytical system has not yet been derived for this film. Integral densities have the disadvantage that they do not show the characteristics of individual layers, as analytical densities do, because the dyes each have some absorption in the regions of maximum absorption of the other dye. Also, the superposition of the three curves does not necessarily indicate visual neutrality as with analytical densities. However, the differences in densitometry are not of major significance, except for the detailed analysis mentioned above, and the curves given do indicate that we have come close to the goal of achieving neutrality for balanced exposures.

For those who do not have access to ma-

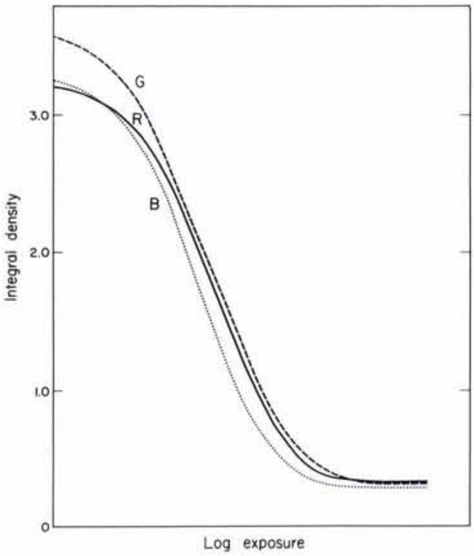


FIG. 8. Sensitometric characteristics when exposed through a KODAK WRATTEN Filter No. 3.

chine processing or who wish to do their own, the film can be processed in Process E-4 chemicals. The sensitometric curves for this process show that the contrast is somewhat higher, but that the color balance is not significantly different than from machine processing.

On the basis of a rather limited number of aerial photographic tests, we estimate that the Effective Aerial Film Speed is about 40, which makes the film intermediate in speed between KODAK EKTACHROME MS AEROGRAPHIC Film 2448 (ESTAR Base) and KODAK EKTACHROME EF AEROGRAPHIC Film (ESTAR Base) SO-397.

The resolving power is 100 lines per mm at a test-object contrast of 1,000 to 1. The RMS granularity is 21.

AERIAL PHOTOGRAPHIC TESTS

Several aerial tests have been made with the experimental film. In all of them, comparison photographs were made on a regular color film, KODAK EKTACHROME MS AEROGRAPHIC Film 2448, and on another experimental film made by leaving the blue-sensitive, yellow-forming layer off a regular reversal color film. The latter film thus had two layers, one sensitive in the green spectral region, and the other in the red.

The camera system used for the tests consisted of a bank of four Hasselblad cameras fitted with 80-mm Planar lenses and 70-mm film magazines. They were mounted in the aircraft facing vertically, and a control system was used which provided simultaneous exposures in all cameras. The fourth camera was generally utilized to test a different coating of film, a different filter, or to expose experimental film for different processes.

In each of the tests, exposure series centered on the expected optimum were made with each film. In addition, various sharp-cut-off WRATTEN Filters, including Nos. 2B, 2E, 3 and 4, were used with the new film to narrow the sensitivity bandwidth of the magenta-forming layer, and to determine which provided optimum color balance.

The first test was flown south of Key West, Florida in the area between Sand Key and Western Sambo. This area contains a considerable amount of bottom detail at depths ranging from a few feet to over 100, often within relatively short distances of each other. Plate 1 includes photographs of an area slightly WSW of Western Sambo photographed on the three films mentioned. Also included is a section of the nautical chart covering the same area to show the depths of the bottom features. The superior ability of the new film to record the underwater detail is quite evident. It is also obvious that both the experimental film and the regular color film show more detail than does the film in which the blue-sensitive layer was omitted.

As was predicted earlier, inspection of the normal-color and minus-blue films showed that almost no underwater detail was recorded by the red-sensitive layers, thus justifying our decision not to include such sensitivity in the new film. It is interesting to note that the specular reflectance from the water is somewhat less noticeable in the photograph made with the water-penetration film than with either of the other two. Study of the individual layers indicates that some of this is due to the red sensitivities of the two films, which record more surface detail; some to differences in the magenta records, because they are records of different spectral regions; and some may be caused by the greater proportion of underwater detail to surface detail in the water-penetration film.

Two other tests were flown in the area north and west of Martha's Vineyard, with similar results being obtained. Here, though, the depths varied from a few feet to about 30 feet, and the results seemed to indicate that because of turbidity, not much greater penetration could be expected in this area.

Conclusions

The improvement in the water-penetrating ability of a color film designed specifically for the purpose has been demonstrated with aerial photographs made in two quite dissimilar areas. The combination of optimum sensitivities and a dye set and color balance which provides maximum discriminating ability has resulted in an experimental film which is superior to both a regular color film and to a film made by omitting the blue-sensitive layer from a regular color film.

There are several obvious applications for such a film, such as mapping coastal areas, underwater obstructions, water depths, and obtaining data on currents and tides. Direct measurement of the two layers of the photographic images should provide data not only on water depth, but also on the quality or amount of organic matter present in the water. Also, the film should be useful from high altitudes or space, because the use of the WRATTEN Filter No. 3 will prevent much of the contrast-reducing effects of aerial haze. Other applications will undoubtedly become evident once some experience has been attained in the use of the film.

It should be emphasized that the film described in this paper is experimental and there has been no decision by the Eastman Kodak Company regarding commercial availability.

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October Cover Photo

Dear Editor:

I immediately recognized the cover on the October Number. The Survey and Mapping Department has earlier photographs of the mountain, including the most impressive stereo pair I have ever seen. With the vertical exaggeration present in a normal stereoscope, the "hole" down the middle of the mountain is quite fantastic to view, and has greatly impressed (and in so doing, given an idea of stereo photography) thousands of members of the public, schoolboys and students and politicians at numerous exhibitions and departmental tours where the photos have been exhibited.

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