N75-15138

MULTISPECTRAL PHOTOGRAPHY FOR EARTH RESOURCES

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Prepared for the National Aeronautics and Space Administration and subject to Clause 90, Rights in Data.

PREPARED UNDER NASA CONTRACT
NAS9-11188

1972
PRINTED IN THE UNITED STATES OF AMERICA BY
WEST HILLS PRINTING COMPANY, HUNTINGTON, NEW YORK.
COLOR PHOTOGRAPHS PRINTED BY
LEBANON VALLEY OFFSET COMPANY, ANNVILLE, PENNSYLVANIA.

Multispectral Photography for Earth Resources

Dedicated

to

All the individuals responsible for the merger of space

and remote sensing technology.

Preface

"Nothing succeeds as well as a good idea whose time has come" and multispectral photography in the year 1972 is that idea.

This manual has been written for those persons who are involved (or expect to be involved) in the routine applications of multispectral photography with regard to space or aircraft assessment of the environment. Many individuals fall into this category: the users whose prime interest lies in the photo interpretation of the final results, the photo technicians whose principal concern rests with the precision processing of multispectral imagery, the student who desires to know what multispectral photography is all about, and the aerial photographer who wants to broaden his background.

There have been numerous remote sensing books written for the engineers, designers, photographers, and photo interpreters of aerial photographic systems, but there has been little or no information available for those who are interested in applying multispectral concepts to their own problems and who may not have an aerial photographic background. This manual has been written for them. We solicit any comments, suggestions, or criticisms of the readers.

The authors wish to express their deep appreciation to those individuals who provided unmeasurable assistance in the preparation of this text: Fred Pearce, NASA Manned Spacecraft Center, Carl Anderson and Richard Rehrig of Spectral Data Corporation, and Peggy Stollar of Long Island University.

Special thanks to John Wiley & Sons, Inc. and Morgan & Morgan, Inc. for permission to use illustrations from their publications.

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CHAPTER 1

INTRODUCTION

Purpose of Manual

There is little doubt in anyone's mind that the photographic interpretation of a complex ground scene is greatly facilitated by the use of color photography. In the earth resources disciplines, where the phenomenon is often very subtle, the use of black-and-white photography has been almost totally replaced by the use of color systems, and for a good reason. Physiologists have told us that the normal eye-brain combination can detect some 7.5 million different colors, while it can sense only 200 different shades of gray. However, as often happens, the phenomenon to be detected is even too subtle to be "seen" on conventional color and color infrared films, so a new technique called multispectral photography has been developed to enhance small color differences between specific items of interest. Unfortunately, multispectral photography has been used only in research efforts to demonstrate its application to earth resources problems. The rather spectacular results which this technique produces have generated a worldwide interest and enthusiasm for employing it as a new remote sensing tool.

Because of the accuracy necessary in the exposure and processing of multispectral imagery, conventional aerial photographic procedures are inadequate to assure meaningful results. Hence, much of the multispectral photography obtained by those who have failed to observe the required photographic procedures is disappointing at best.

The purpose of this Manual is twofold. First, it is intended as a guide to producing accurate multispectral results for earth resources applications. An established procedure is presented in an effort to minimize "learning time" and to eliminate unnecessary research effort which has already been performed. The second purpose of the Manual is to present to the reader the theoretical and analytical concepts of both color and multispectral photography in order to facilitate an understanding of the established procedures. This Manual has been written in a very simplified manner; the bibliography should be referred to for a more detailed treatise of the concepts included herein.

1.1 What is Color?

In order to form an accurate concept of color it is helpful to consider, initially, the entire electromagnetic spectrum. This spectrum consists of radiant energy travelling through space in the form of *waves* of various *lengths*. The longest of these waves is radio broadcast, while the shortest is cosmic rays. It should be noted that each part of the electromagnetic spectrum has *exactly* the same nature and differs from the other parts only in wavelength (length of one wave). The upper portion of the following diagram (Figure 1) represents the major divisions of the electromagnetic spectrum in which the wavelength of the energy is given in nanometers (10^{-6} meters). That small wavelength region from 380 to 760 nm consists of visible radiant energy called light and is shown in the lower part of Figure 1. This range of visible radiant energy may itself be subdivided into many components, each one of which can be described as a color. For example,

Wavelength Range	Apparent Color
380 nm to 430 nm	Violet
430 nm to 475 nm	Blue
475 nm to 510 nm	Cyan
510 nm to 560 nm	Green
560 nm to 590 nm	Yellow
590 nm to 620 nm	Orange
620 nm to 760 nm	Red

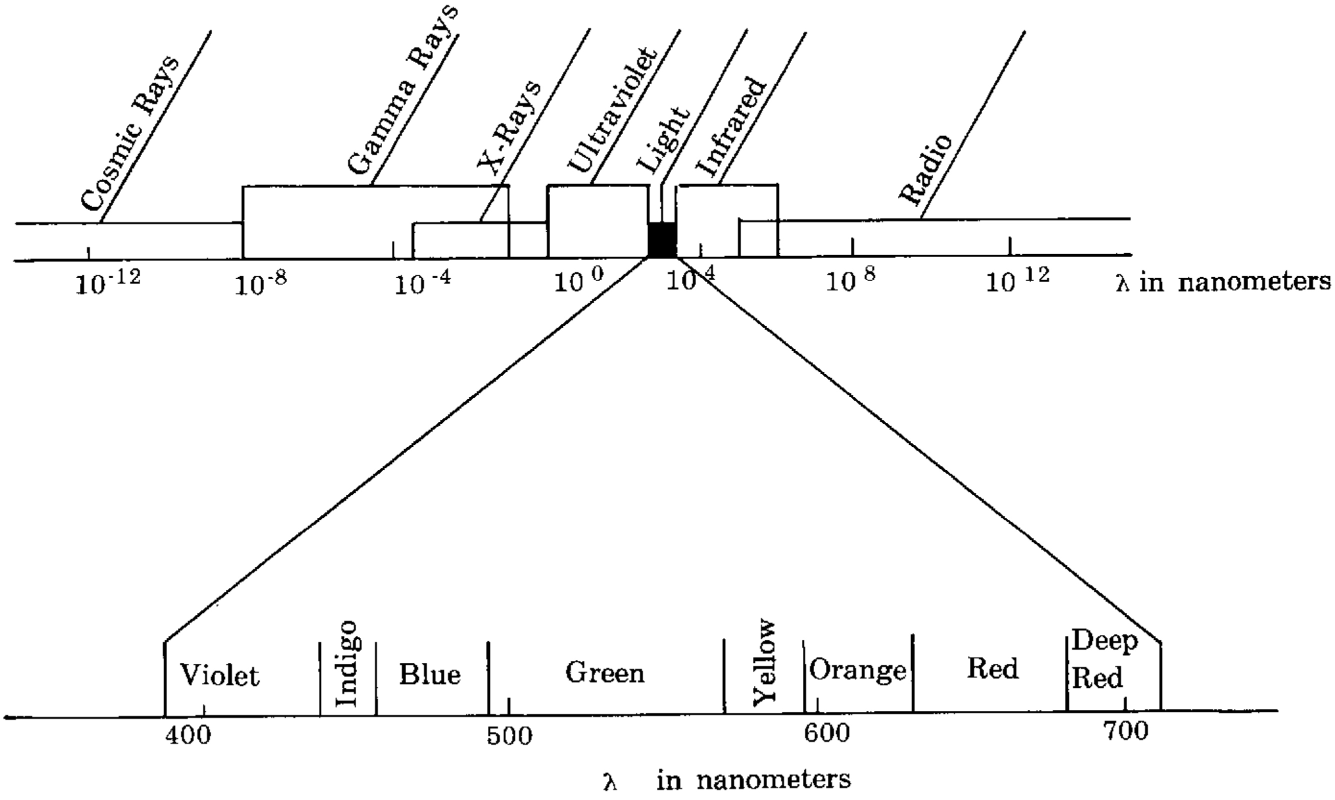


Figure 1. Parts of the electromagnetic spectrum and an expansion of the visible spectrum.

The definition of color may be given as that aspect of visual perception by which an observer may distinguish between objects having the same size and shape. There are three characteristics of color: hue, saturation, and brightness.

Hue is that characteristic which causes one to describe a color as red, yellow, green, blue, etc. However, in addition to hue, all colors consist of other characteristics. Saturation is that property of a color which indicates the purity or amount of white contained in the color. The horizontal group of paint swatches in Plate I shows a red hue at several levels of saturation, the most saturated (or purest) being level 6 and the most desaturated (white) being level 1. It is interesting to note that as the hue approaches the limit of desaturation, the color becomes a neutral white or gray. More specifically, saturation is the ratio of the amount of hue in a color to the total amount of energy in a color. For example, if a color contains three units of blue light and six units of white light, then:

$$\text{Saturation} = \frac{3\text{ units (blue)}}{9\text{ units (total)}} = 33.33\%$$

In other words, this color combination is only about 33 percent pure blue.

The third major characteristic of color is brightness. Brightness is a measure of the amount of black in a color. It is that attribute, for example, which makes scarlet red different from maroon red or royal blue different from navy blue. Referring again to Plate I the vertical column of colors differs only in brightness. As a hue becomes less bright, it approaches pure black.

Most color photographic processes are designed to accurately reproduce the hue, saturation, and brightness characteristics of any color which the eye perceives. In other words, it is the intent of color photography to simulate the visual mechanism of the eye and to produce a "hard copy" of the color images for future reference. There are two main approaches to this task:

1. Additive color photography which was the first method by which a scene could be reproduced in full color.
2. Subtractive color photography which today is the technique upon which most commercial color processes are based.

The theoretical aspects of the additive and subtractive production of color will now be presented together with their respective techniques called multispectral and multilayer color photography.

1.2 Additive Color Formation

In 1861, Clark Maxwell noted that the visual appearance of a color could be matched by a correct mixture of three different light sources: red, green, and blue. He also realized that these primary colors could be mixed in varying proportions to produce almost every conceivable color. This concept is best illustrated in Plate II. The combination of red and green light results in a yellow being produced and by adding together the blue and green beams, a cyan color is produced. The addition of blue and red light yields magenta, while the mixture of all three primaries produces white. It should be noted that additive production of color is dependent upon the individual projection of each primary onto a common screen. Maxwell applied this concept to the photographic process and generated what is now known as multiband or multispectral photography.

1.3 Multispectral or Additive Color Photography

Multispectral or additive color photography consists of three basic tasks:

-- The color analysis or separation of the scene by use of filtered photographs.
-- The processing of the film.
-- The color synthesis or recombination of the photographs in an additive projection system.

Suppose it is desired to photograph a series of different colored patches using additive techniques and the configuration of the scene is that of Figure 2a.

The following procedure is used to produce the required separation negative films shown in Figure 2b:

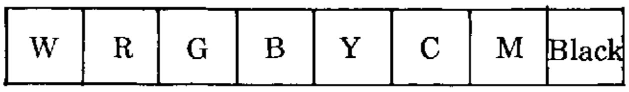
-- The scene is photographed with a camera using black-and-white film and equipped with a red filter in front of the lens.
-- Without moving the camera, the red filter is replaced by a green filter and the color patches are again photographed with black-and-white film.
-- The green filter is then replaced by a blue filter in front of the lens and the scene is photographed once again.

Each of these three pieces of film is developed as a negative and will have densities as illustrated in Figure 2b.

These negative films are then printed into positives before being projected in additive color. Naturally, the densities (or grayness) of the images in each positive film will be opposite of what they were in the negative as shown in Figure 2c.

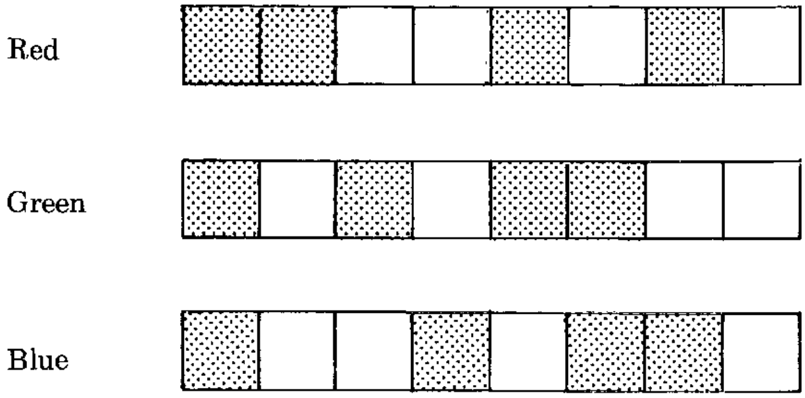
These three positive films are now ready for recombination or synthesis onto a viewing screen. Each is placed into a separate projector (shown diagrammatically in Figure 2d); the projector containing the red record has a red filter over the lamp, the projector containing the green record has a green filter over the lamp, and the projector containing the blue record has a blue filter over the lamp. The projectors are moved close together so that the three projected film images superimpose exactly on the viewing screen. Referring now to the additive mixtures shown in Plate II, the projected combinations of the three positive films will yield the final scene reproduction shown in Figure 2d.

Patch Color	Synthesized or Additive Color
Black	In none of the three positive films is this image clear; hence, no light is projected on the screen so that the color of this color patch is *black*.
White	This image is clear in all three records; hence, red, green, and blue light will be projected in this area. We have seen from Plate II that the combined effect of red, green, and blue is *white*.
Red	Only the red positive record has this image as clear; red will be projected and the green and blue light will be stopped by the densities on their films.
Green	The green positive record has this patch sample as clear; no red or blue light will be projected onto the screen so that the image will appear as pure *green*.



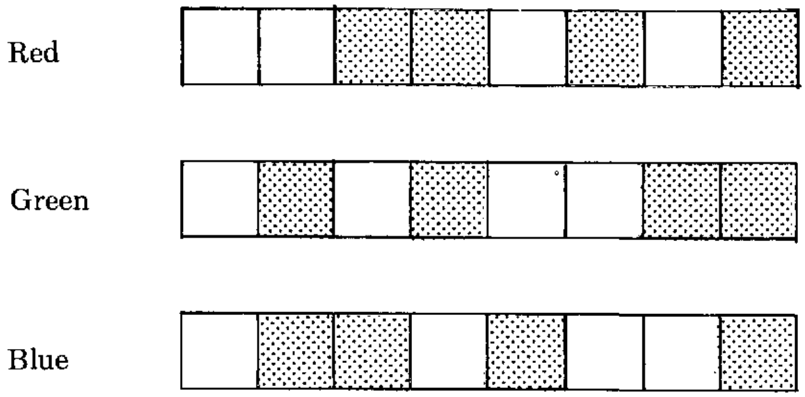
Original Scene

Figure 2a



Cross-section of multispectral negative records after silver halide grains have been exposed in the camera and developed.

Figure 2b



Cross-section of multispectral positive records after printing from the negative records and processed.

Figure 2c

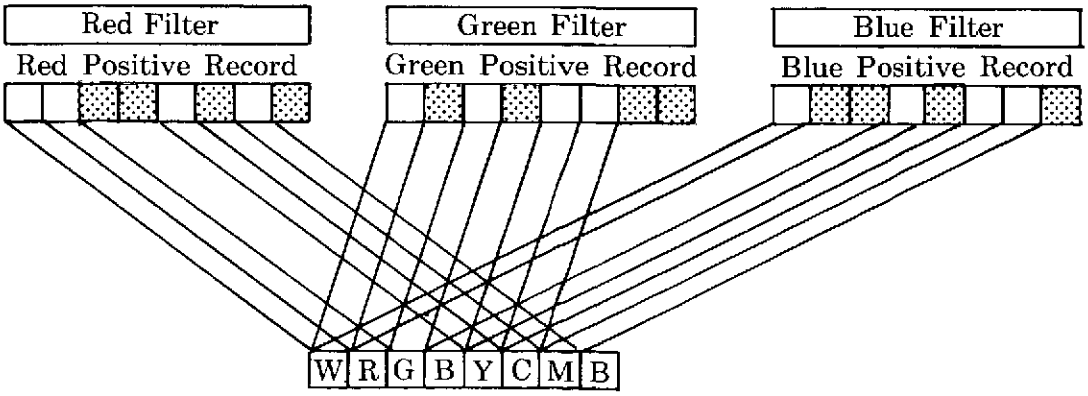


Figure 2d
Additive color reproduction of the original color patches.

Figure 2. Reproduction of colors using additive multispectral techniques.

Blue	Only the blue positive record is clear at this image; hence, green and red are not projected and the patch appears *blue.*
Cyan	Both the green and blue positive records show that the image of this patch is clear; no red light is transmitted. The addition of green and blue lights produces *cyan.*
Yellow	The red and green positive images of the yellow patch are clear.Plate II illustrates that the addition of red and green lights is *yellow.*
Magenta	The green record is opaque (dark) for this last color sample. The blue and red records are clear and will transmit these colors to produce *magenta* on the screen.

We have seen, then, how a single scene composed of many colors can be additively reproduced accurately by:

1. Separating, onto three pieces of black-and-white film, the reflected energy in three spectral regions; namely, red, green, and blue.
2. After processing the film to positives, they are projected using the same primary filters through which the photos were exposed.
3. The superimposition of these three positive photos onto a common screen produces a full color reproduction of the scene.

One should note that additive color produces not only the primaries used in projection, but a wide gamut of secondary colors as well. A more detailed discussion of additive color production will be given in Chapter 3 with the subject of color matching.

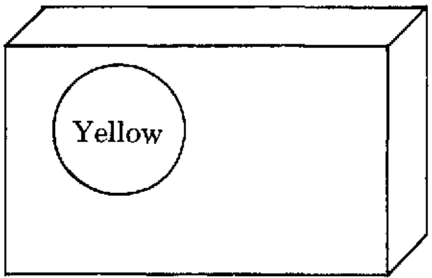
1.4 Subtractive Color Formation

Given a beam of white light (consisting of red, green, and blue components), it is possible to produce color by removing or subtracting from that beam, light of various wavelengths. Consider Figure 3a in which a circular yellow filter, which transmits all spectral colors except blue, is placed over a light box. Only yellow light is transmitted through the filter. If a magenta filter, which passes all colors except green is placed over part of this yellow, then only red light is transmitted through the combination (see Figure 3b). Similarly, if a cyan filter, which freely transmits the blue and green spectral components, is placed over a portion of the yellow filter, then only the color green will be transmitted through the combination (see Figure 3c). Overlapping the cyan and magenta filters will permit blue light to be transmitted as shown in Figure 3d. The superimposition of all three filters, shown in Figure 3e, transmits no light, thereby yielding black. One should note that in subtractive color theory, the primaries are *opposite* those foradditive color production, as shown in Figure 4.

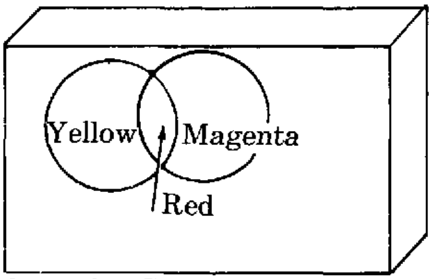
Primaries

Additive	Subtractive
Red	Cyan
Green	Magenta
Blue	Yellow

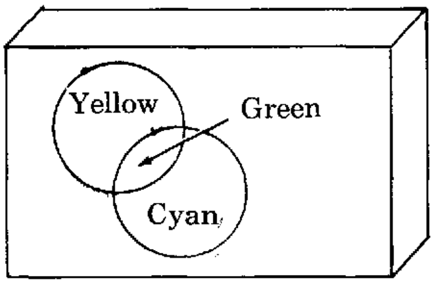
Also, no individual projection of the subtractive primaries takes place; the primary colors are placed in physical contact with each other and the combination is projected.



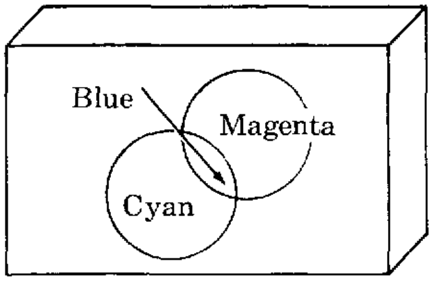
Yellow Primary
Figure 3a



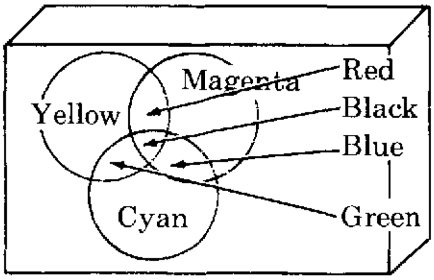
Subtractive Combination of Yellow & Magenta Primaries
Figure 3b.



Subtractive Combination of Yellow & Cyan Primaries
Figure 3c



Subtractive Combinations of Magenta, and Cyan Primaries
Figure 3d



Subtractive Combination of Yellow, Magenta, & Cyan Primaries
Figure 3e

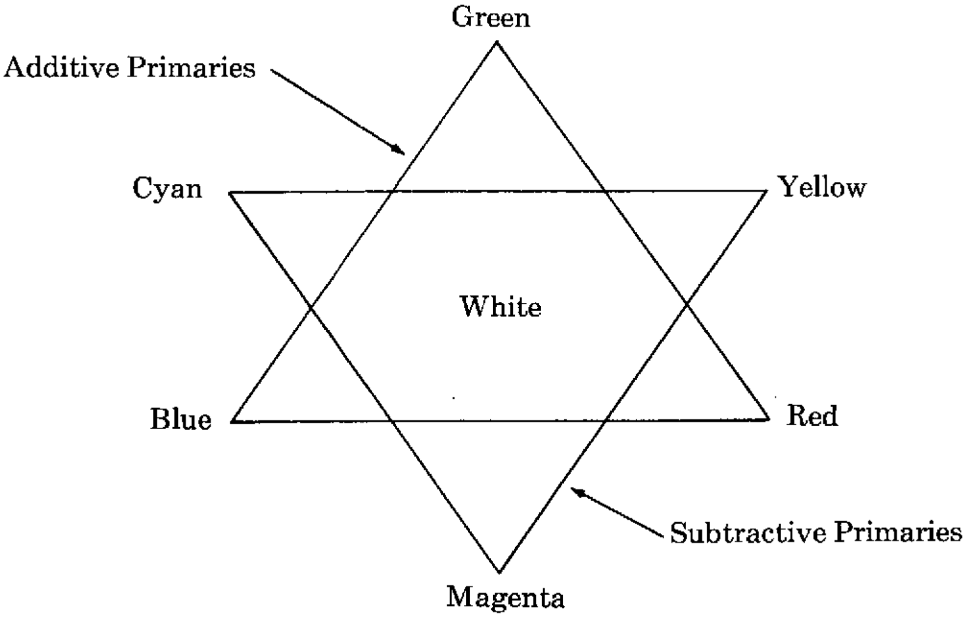


Figure 4. Additive and subtractive primaries are opposite each other or are complimentary colors.

1.5 Tripack or Subtractive Color Photography

All color films (negative, as well as reversal types) consist of three emulsion layers, each one of which is sensitive to a different spectral region. In addition, each emulsion contains a dye which is the compliment of the color to which the emulsion is sensitive. That is, the blue sensitive layer contains a yellow dye, the green sensitive layer contains a magenta dye, and the red sensitive layer contains a cyan dye. A cross-section of a color film is shown in Figure 5. Referring to Figure 5a, any blue light which is incident upon the film will expose the top emulsion layer. No blue light can pass through this top layer and sensitize the other two emulsions due to the presence of a yellow filter between the top and middle layers. Green light falling on the film will not sensitize the first emulsion because of its wavelength. It will, however, pass through the filter (since a yellow filter transmits both red and green light) and sensitize the green sensitive emulsion. Similarly, red light will not effect the blue and green sensitive layers, but will pass on through these emulsions exposing the third or red sensitive layer. White light, of course, will sensitize each of the three emulsions since it is composed of essentially equal parts of red, green, and blue light. Conversely, the absence of reflected light (black) will sensitize none of the emulsion layers. The remaining colors shown in Figure 5a, namely, yellow, magenta, and cyan, will record proportionately on more than one emulsion. For negative color films, the color dyes of each layer are formed in the development stage of processing in the following way. Chemical substances known as couplers are incorporated into each emulsion. These couplers combine with the oxidation products resulting from a reaction between the developer and the exposed silver halide. The dye is formed in each layer in proportion to the amount of silver developed. The developed

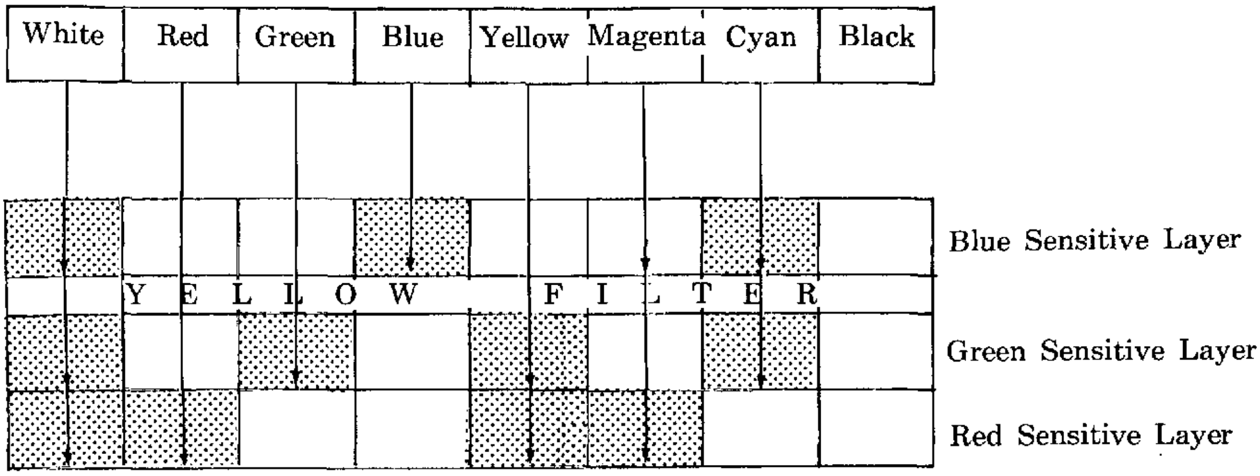


Figure 5a. Exposure of color patches onto a negative film as seen in cross-section.

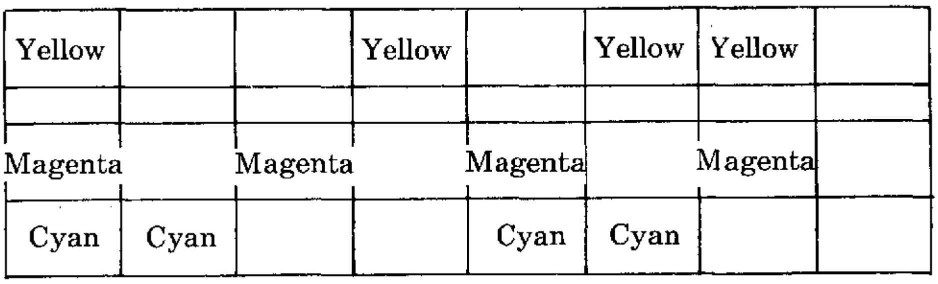


Figure 5b. Color negative film after silver grains have been bleached leaving the dye image.

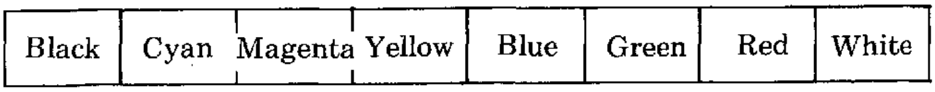


Figure 5c. Resultant color negative image generated from patches shown in Figure 5a.

Figure 5. Reproduction of colors using negative films.

silver grains are then bleached out, leaving only the negative dye images, as shown in Figure 5b. The resultant negative transparency (Figure 5c), is essentially complimentary to the original scene in *both* tone and color. The overall orange appearance on the final negative film is caused by the residual yellowish and reddish color couplers which provide automatic masking for color correction.

Color positive emulsions basically perform in the same way that color negatives do. However, during the development process, the film undergoes reversal which generates the positive images. Referring to Figure 6a, the color positive film is exposed to a series of color patches. The *first developer* converts the camera exposed silver halide particles into metallic silver. After this development has been completed and the processing has been stopped using a "stop bath", the film is either exposed to room lights or chemically fogged. This procedure causes a reversal effect to take place in the camera-exposed silver particles and the remaining unexposed silver halide crystals are now exposed for the first time. This is shown in Figure 6b. The development by-products react with the dye couplers in the film emulsion to form the cyan, magenta, and yellow dye images shown in Figure 6c.

The white patch is rendered clear in the final reversal image of Figure 6d, while the black patch will be opaque since the subtractive combination of yellow, cyan, and magenta is black. Referring to Figure 3, the remaining subtractive combinations will be seen to result in the correct color reproduction of the original scene shown in Figure 6a.

One further color film is worth describing in this section; namely, color positive infrared. Unlike the color reversal film just discussed, color infrared is sensitive to the green, red, and near infrared portions of the spectrum, instead of the usual blue, green, and red. A yellow filter is placed in front of the camera lens to assure that no blue light will be imaged. Figure 7a shows a subject which reflects all visible light, as well as infrared. After exposure in the camera, the film layers are sensitized as shown in Figure 7b. Unlike the usual color reversal films, the infrared sensitive layer contains a cyan dye, the green sensitive layer contains a yellow dye, and the red sensitive layer contains a magenta dye. After reversal exposure and color processing, the dye images of Figure 7d result. The blue portion of the scene is rendered black, the green portion is blue, while the reds are reproduced as green and the infrared as red (see Figure 7c). The resulting transparency is a false color presentation of the subject and the addition of the infrared light component makes this film quite useful for earth resources studies. Like other color films, however, it does have some serious limitations which will be discussed in the next chapter.

When the infrared component of, say, vegetation is high, it tends to predominate over the natural green color so that the foliage appears brilliant red on color infrared film. As the infrared reflectance decreases, more equal amounts of green and infrared may be imaged on the film. This causes a shift in the foliage color from bright red to magenta.

1.6 Summary

- The electromagnetic spectrum consists of radiant energy of different wavelengths; the wavelength interval from 380-760 nm is known as light and is composed of different colors.
- Color has three properties: hue, brightness, and saturation.

White	Red	Green	Blue	Yellow	Cyan	Magenta	Black

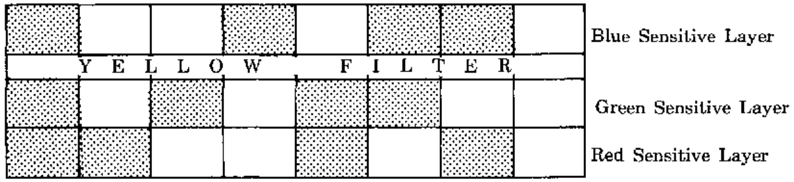


Figure 6a. Cross-section of positive color film after exposure to color patches above.

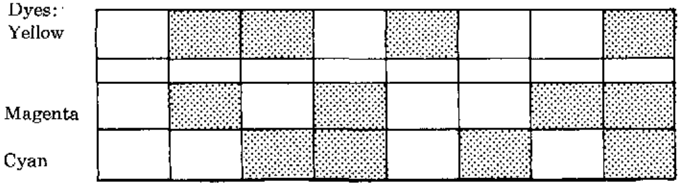


Figure 6b. Cross-section of positive color film after chemical fogging of the emulsion.

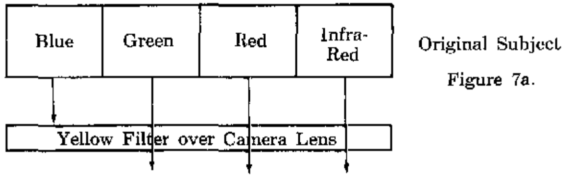
	Yellow	Yellow		Yellow			Yellow
	Magenta		Magenta			Magenta	Cyan
		Cyan	Cyan		Cyan		Magenta

Figure 6c. Color reversal film after silver grains have been bleached leaving the dye image.

White (Clear)	Red	Green	Blue	Yellow	Cyan	Magenta	Black

Figure 6d. Final color reversal image generated from patches shown above.

Figure 6



Original Subject

Figure 7a.

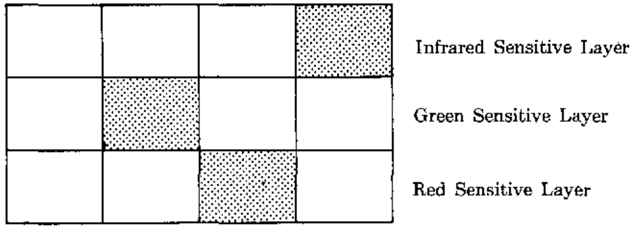


Figure 7b. Cross-section of positive color infrared film after exposure to original scene.

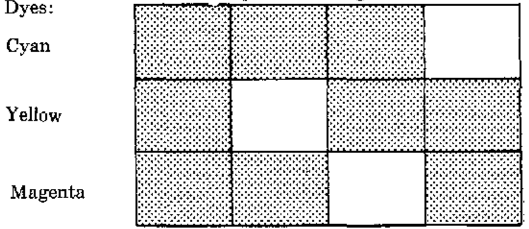


Figure 7c. Cross-section of positive infrared film after reversal.

Cyan	Cyan	Cyan	
Yellow		Yellow	Yellow
Magenta	Magenta		Magenta

Figure 7d. Color infrared film after silver grains have been bleached leaving dye images.

Black	Blue	Green	Red

Figure 7e. Final color infrared image generated from original scene.

Figure 7. Reproduction of colors using positive reversal film.

- Color photographic processes are designed to accurately reproduce hue, brightness, and saturation.
- Multispectral photography is based upon the additive color theory.
- Multispectral photography consists of imaging a scene with three primary filters and recombining them on a viewer screen.
- Tri-pack color films employ the subtractive principal of color reproduction.
- Negative color films are usually used for production of photographic prints.
- Positive color or reversal films produce a positive transparency directly.
- It is possible to photograph the near infrared spectral region with the use of specially sensitized materials.
- Additive and subtractive primaries are complimentary.

CHAPTER 2

CAPABILITIES AND LIMITATIONS OF COLOR AND COLOR INFRARED FILMS

The human eye is a great deal more sensitive to differences in color than it is to differences in brightness; as a result, a 10 percent error in the brightness of a black-and-white photograph will not be particularly noticeable to the eye. However, a 10 percent error in, say, the blue balance of a color photo can degrade warm facial colors into shallow corpse-like tints. To assure against this, the subtractive tripack system of color photography must provide accurate controls at every stage. Cumulative color errors of 5 percent are generally considered to be the maximum since greater errors can cause distortion and even complete loss of a color image. In spite of this, the manufacturers of color films produce emulsions which, by and large, yield good results. This is accomplished by their control of the imperfections at every stage: the film manufacture, the recommended exposure time, and the exact conditions of color film processing which they specify in detail. However, before selecting an emulsion for detailed scientific experiments, it is essential that one understand the exact limitations and capabilities of color films.

2.1 Capabilities of Color Films

The greatest advantage of color tripack emulsions over multispectral additive photography rests in the ability of the photographer to obtain a color reproduction of the scene within a reasonable length of time and with the minimum amount of inconvenience. The photographer need only worry about the lighting balance and the exposure in order to guarantee himself reliable scene reproduction. In addition, a great number of color film processing facilities exist, most of which are able to maintain the precise processing control necessary in color work so that even this burden is removed from the user. Regardless of whether negative color emulsions (producing prints) or reversal color films (transparencies) are used, there exist no major requirements for equipment with which to analyze the results. A light table or projector for viewing transparencies is the exception.

Since three layers of emulsion are coated onto a single base, light falling onto the film and exposing the three layers is, of necessity, registered automatically. That is, there exists no color fringing around the edges of objects such as one often sees in printed photographic material such as journals, textbooks, and comic pictures. This factor has obvious advantages, especially in aerial photography taken at high altitudes.

The final resolution of an additive color presentation is less than a color emulsion owing to the fact that multiple images must be superimposed manually through a series of projectors. To understand the resolution advantage of color films over multispectral presentation, the following example is given. Assume that a reversal color photograph, as well as three multispectral images of a scene have been taken at the same scale and that the resolution of each photo is 40 lines/mm. The color film is projected at a magnification of 1:1, as are each of the multispectral records. After superimposing the multispectral images as shown in Figure 8, the resultant composite will be the color transparency.

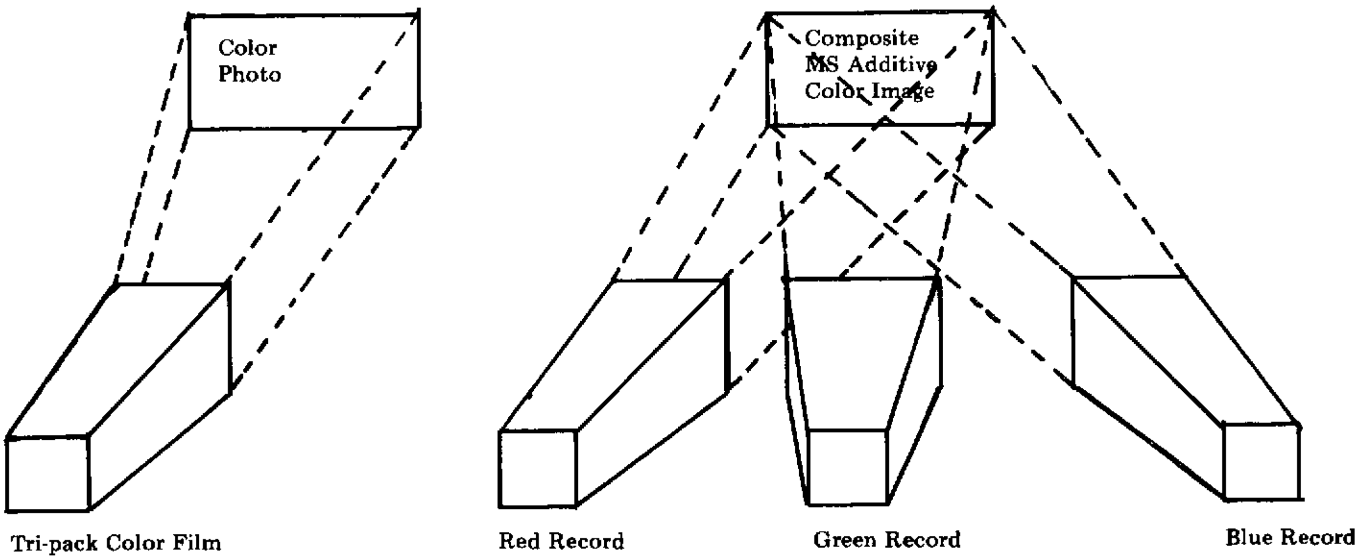


Figure 8. Projection of color photo and additive color presentation for comparison of resolution.

Neglecting any resolution loss caused by the projector optics, the color film image on the screen still has a resolution of 40 lines/mm. The multispectral presentation will only have a resolution of 40 lines/mm if the projectors are set up correctly to within .0005 inches of each other.

Manufacturers of three-layer color films generally quote the resolution of their emulsions in the technical data sheets. For example, Eastman Kodak Ektachrome M-S film # 2448 has a resolution of 80 lines/mm at a contrast of 1000:1 and 40 lines/mm at a contrast of 1.6:1. Although contrasts of 1000:1 are almost never encountered in aerial work and contrasts of 1.6:1 are common, the resolution of the color film is still excellent.

Color films are exposed through single lens cameras which, unlike multispectral multiple lens or multiple camera systems, are easier to operate, cheaper, and require no special calibrations. Use of tripack films for the production of color photographs represents the ultimate in simplicity. Providing the lighting and exposure are correct, color or color infrared photos produce acceptable results which are intended to be pleasing to the eye and to approximate the colors in the scene.

2.2 Limitations of Color Films

Tripack color emulsions are not, however, without their limitations and disadvantages, especially when they are used for scientific purposes such as aerial photography.

One of the major difficulties encountered with the use of color films is the fixed exposure ratio of each layer to light. For example, if one is primarily interested in reproducing the blue parts of a scene on a color film and there is only a small amount of blue light being reflected, the red and green reflected light will mask or even eliminate the effect of the blue. Unlike tripack films, additive color photography is not hampered by this situation. In the latter case, the imagery is obtained using separate lenses and one would merely open up the iris diaphragm of the blue lens and close down the red and green apertures. The final color of such a combination would then possess an adequate amount of blue.

By way of illustration, consider a scene in which the red and green components of the reflected light are 16 times greater than the blue component. Using a color film, the red and green emulsion layers would receive 32 units of light for every 2 units received by the blue layer. In terms of exposure, this difference is 4 stops which is certainly sufficient to mask the blue light reflected from the scene. If, however, a multispectral photograph of the same scene were taken, the blue lens could be set at f/4 and the red and green lenses at f/32. The blue multispectral image would then receive exactly the same exposure as the red and green images. In other words, the blue component of the scene would appear to be as bright as the red and green. The result of such a procedure has the effect of "enhancing" the subtle color in the scene, i.e. blue.

The second major drawback of color films is that each layer is sensitive to a fixed range of color; namely, red, green, and blue (or in the case of color infrared film, green, red, and infrared). It may be impossible, therefore, to tell the difference between two different color greens. The green layer may record both colors identically so they will be indistinguishable. For example, consider the case of two water masses identical in color except for two differences in the green spectral region. Their reflectance curves might be similar to those shown in Figure 9. Using conventional color films, water mass A and water mass B would not be distinguishable. However, using additive color it would be possible to filter one camera lens from 550 to 565 nm and another lens from 580 to 600 nm. After making black-and-white transparencies of each image and placing them in an additive color viewer,

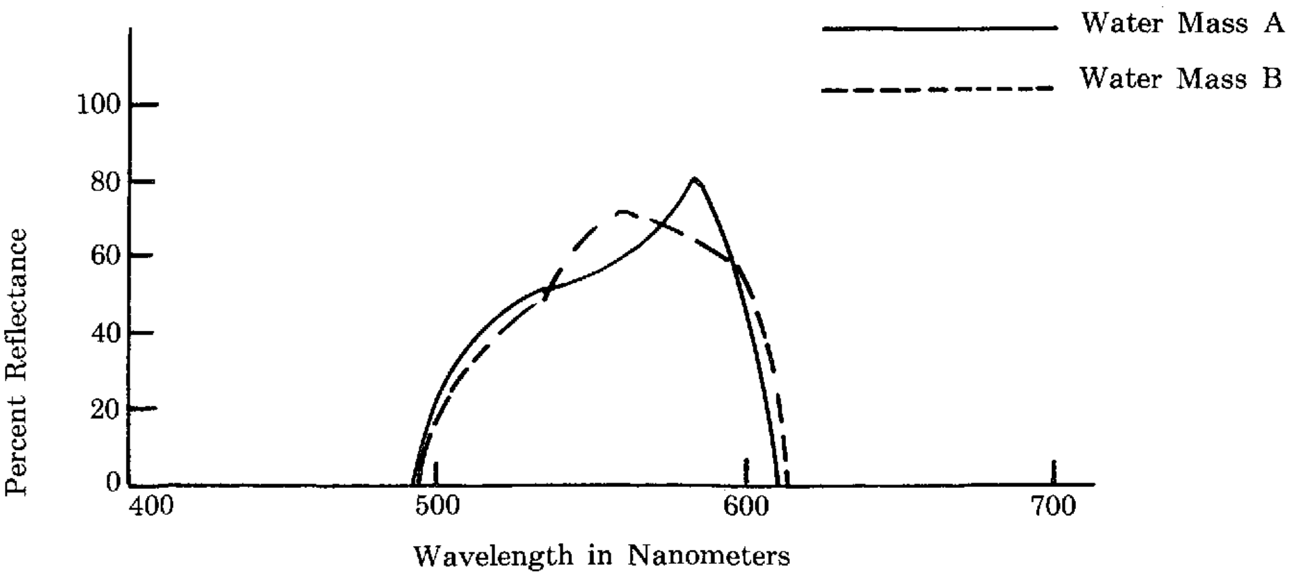


Figure 9. Subtle spectral distribution difference between two water masses.

one of the photos can be projected as green and the other as red. The color differences between the water masses will now become obvious, whereas they would be indistinguishable on color emulsions. Unless it becomes possible to alter the wavelength bands, sensitivities, and exposure ratios of each layer, conventional color emulsions will not be extensively employed in the detection and identification of subtle environmental color differences.

Another major disadvantage of color films lies in the fact that once the film is exposed and processed there is almost no way to alter the results. They are fixed and inflexible. The photo interpreter must analyze the film as presented to him without control over the density of color of the imagery. Additive color photographs have no such limitation, since the blue, hue, brightness, and saturation of each image can be altered in the multispectral projector.

Color emulsions are somewhat hampered by poor keeping qulaities which can cause differential ASA speed changes between the layers. This will affect the color balance of the resultant imagery and, since there is no way to control either the density or the contrast of each layer, correction of this problem is almost impossible.

The inherent difficulties associated with exposure and processing of color films are discussed later in this chapter. Lengthly processing times, as well as precise requirements for color film development, can be disadvantageous when color imagery is required without the optimal processing conditions. Often when operating outside the United States, users cannot find adequate processing facilities or cannot develop their color films because of poor water conditions, temperature, etc. They are required to ship their color films to the States for processing at a high cost and long delay.

In spite of these disadvantages, good to adequate color reproduction is possible using a tripack or multilayer emulsion, if certain requirements are satisfied both before and after exposure of the film in the camera. Some of the factors which affect the reproduced color and which will now be examined are:

- film storage prior to exposure
- photographic exposure
- the quality or color characteristics of the illuminant
- film storage after exposure and before processing
- processing conditions
- final viewing conditions for the transparencies

2.3 Controllable Causes of Color Error

2.3.1 Film Aging

The manufacturers of multilayer color films naturally desire that their emulsions produce the best possible results at the time of exposure and processing. Hence, they are generally quite concerned about aging of the film; color emulsions are perishable in that their characteristics change with time and environmental conditions. Since color tripacks consist of three emulsion layers instead of one (as is the case for black-and-white films), changes in temperature and storage conditions will affect each of three layers somewhat differently. The result is that emulsion aging is considerably more apparent in a color photograph than on a black-and-white one.

Using experience and statistical studies, color film manufacturers have ascertained the *normal* conditions to which an emulsion will be subjected between its manufacture and its time of use. Color film packages contain an expiration date based upon the assumption that the film was subjected to these *normal* conditions. If the storage conditions were worse than normal, the film would naturally prove unsatisfactory prior to the stated expiration date. Conversely, if the film had been stored in a freezer at some temperature well below the suggested storage temperature of 68°F, then the film would still produce satisfactory color long after the expiration date had passed.

In temperate climates no special precautions for film storage are necessary; this assumes that the film is kept in its moisture-proof packing until just prior to use. If the packing is removed, the film must be kept free from moisture, preferably in a sealed container with a drying or desicating agent such as silica gel. If it has been stored in a refrigerator or freezer, the film should be kept in the moisture-proof wrapping until it becomes temperature stablized with the environment. Storage in such a container also keeps chemical fumes (which exist in areas used for storing developer, hypo, fixer, etc.) from deteriorating the unexposed emulsion. High humidity also causes and increase in the rate of change of the color film emulsion layers. However, it should be noted that subjecting the latent image to high temperature and/or high humidity after exposure, but before processing, will cause *greater* undesirable effects in the image than the same conditions would cause in unexposed film.

2.3.2 Exposure of Color Films

There are two basic types of tripack color films: the negative emulsion (which is generally used for the production of positive prints) and the reversal positive emulsion (which yields a positive transparency directly). Accordingly, these two film types require different camera exposure controls to create accurate scene reproduction. The exposure considerations for negative materials will be considered first.

Color Negatives:

Unlike the reversal transparency, a color negative is not the end product itself, but only the means to an end — namely, a color print. In this sense, the exposure requirements for negative emulsions are considerably less stringent than those for reversal materials. That is to say, an error in the exposure of a negative color film may yet be corrected in the printing stage in order to alter both the density of the images and the color balance. Printing a positive from a poorly exposed color negative does, however, require a series of complicated tests to determine the exposure and color balance corrections necessary.

In order to reproduce correct tone and color, the negative color film must record the minimum density (darkest shadows), as well as the maximum density (brightest highlights) on the straight line portion of the characteristic curve. There is, however, no constraint on the *position* of the maximum density along the straight line; hence, negative films have considerable latitude towards overexposure and it is much better to slightly overexposure the film if one is in doubt of the exact exposure required.

The brightness range of the scene is very important for negative films since color print material can only reproduce a *limited* brightness range. Any objects in the scene *less* bright than the lower limit of the print material and any objects which are *more* bright than the upper limit of the print material will be distorted. Brightness and color are inseparable in color films; hence, any brightness or tone distortions will cause a distortion in the color of the subject as well. An error such as this cannot be removed during the printing process, since the unbalance exists within the brightness range. Color correction is only possible when we wish to eliminate unwanted color from the *entire* picture, not when we wish to correct the color in the darkest and/or brightest areas. A very small amount of this color unbalance may be removed by reducing the image contrast in the negative, however. Care should be taken that a suitable light meter is used to establish the *minimum* exposure necessary for the darkest shadows. As long as the high and low tones are contained on the straight line portion of the characteristic curve, we are assured that all other brightness or tones of the subject will be in their correct positions on the curve.

Color Positives:

Reversal tripack films are used to yield a positive transparency directly and are, therefore, the final end product. The quality of a reversal transparency will depend upon the conditions present at the time of exposure and little or nothing can be done to improve upon a poorly exposed image. A color transparency must possess *exactly* the right amount of unaltered silver halide in order to produce the positive image, after the negative image has been developed to metallic silver. Gross overexposure, therefore, will cause very little of the unaltered silver halide to remain and there is no chemical which can restore an image which has been dissolved away (as metallic silver) during processing. Moderate overexposure will cause more than the desired amount of silver halide to be converted into metallic silver in the highlights of the image. Hence, a loss of the small detail in these highlights should be expected with moderate overexposure.

Underexposure of a reversal film will leave an excess of neutral dye over the entire positive transparency. Also, there will exist a lack of detail in the dark or shadowed areas and like its counterpart, overexposure, there is no chemical which can restore the loss of detail in these dark areas. The range of exposure over which satisfactory results are obtained is quite small for reversal materials; deviations of between ½ and 1 stop from the optimal exposure are sufficient to cause noticeable color quality losses. It is *essential,* therefore, that an exposure meter be used to determine the correct exposure on reversal films. The only exception to this rule is when exposure is taken *under sunlight* conditions. This is because the exposure of a reversal material is set in order to correctly reproduce the highlights and the exposure of the highlights depends largely upon the intensity of the illuminant. The illuminant, sunlight, is sufficiently predictable for the manufacturer to be able to recommend reliable exposure times which will produce transparencies as satisfactory as those exposed with the aid of a light meter. When, however, the subject is in the shade or an artificial illuminate is used, we must again rely on the use of the exposure meter.

It has been stated that the exposure of a reversal material is selected so as to correctly reproduce the highlights of the scene. This is because highlight details and the lighter tones of a scene attract the attention of the eye due to their relative brightnesses. If exposure were based upon the shadow areas, the amount of dye left in the highlights would depend upon the contrast range of the scene. Hence, we expose for the highlights and let the shadow areas fall where they might.

There is one more interesting aspect of exposing a reversal film for highlights. Generally, the transparency is viewed through a projector or is back-lit with a light box or table. If an error is made by under-exposure of a reversal material, then viewing or projecting it with a brighter light will *increase* the apparent luminosity of the highlights so that it looks as if it were correctly exposed.

2.3.3 Light Source Used for Exposure

The energy distributions of various light sources differ enormously. Figure 10 shows the output of daylight, tungsten, and sunlight as a function of wavelength. Usually it is necessary to employ a color correction filter in conjunction with *both* negative and reversal films so that consistent reproduction of the scene is maintained regardless of the illuminating light. Manufacturers of color films publish the recommended filters for particular film and light conditions. Generally, no two combinations are the same and strict adherence to this published advice is *essential.*

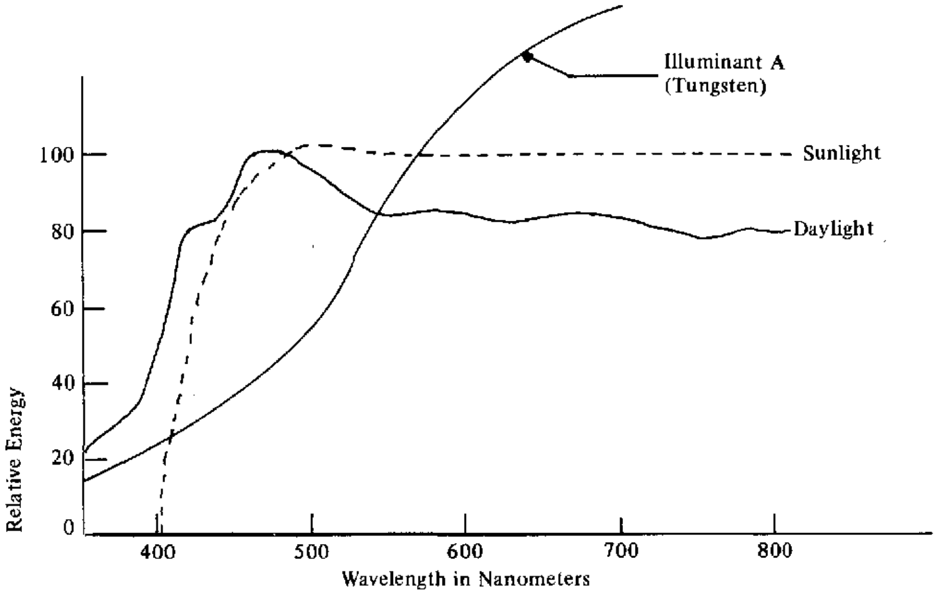


Figure 10. Spectral distribution of daylight, sunlight, and tungsten lamp (Illuminant A).

2.3.4 Color Film Processing

One of the greatest sources of error in the accurate reproduction of color using tripack films rests with the extremely long and tedious development procedure. Processing color emulsions is much more complex than processing black-and-white films and as such requires a high degree of regulation each step of the way. All of the care which is taken to correctly expose the film may be completely lost if the development is not precisely controlled. This includes exact specifications as to:

- processing time
- agitation
- solution temperatures
- correct mixing proportions of chemicals
- solution replenishment

For color development, a rather large number of tanks are required; there should be one tank for each stage of the process. The tanks generally come supplied with a number of holders for sheet film or a reel upon which roll film is wound. Either one permits the film to be quickly transferred from one tank to the next. Although it is possible to use fewer tanks by emptying one solution and refilling the tanks with another, this method is tedious and may appreciably influence the timing of the processing strips. Color emulsions must be processed in total darkness for long periods of time so that an uncomplicated darkroom set-up will assist the operator in maintaining the development schedule, as well as his sanity. For example, Table I shows the processing sequence for negative and reversal color emulsions. The estimated time to complete these steps ranges between sixty and ninety minutes. One can readily understand that a tank for each of the steps mentioned in Table I definitely has its advantages over using the same tank for different solutions by transferring them from storage containers.

Step #	Color Negative	Color Reversal
1	Color Development	First Development
2	Washing	Wash or Stop Bath
3	Stop Bath	Hardening
4	Washing	Washing
5	Bleaching	Second Exposure
6	Fixing	Color Development
7	Washing	Washing
8	Hardening & Stabilizing	Bleach
9	Drying	Washing
10		Fixing
11		Washing
12		Drying

Table I. Procedure for processing negative and reversal color films.

The manufacturer's instructions supplied with color films generally recommend the use of processing kits for development. The pre-measured chemicals which are contained therein are accurately proportional so that by following the mixing instructions *exactly,* the best guarantee of consistent results is offered. *Never* use mixing instructions from a previous processing kit; manufacturers often make minor changes both in the proportions of the chemicals and the timing or mixing instructions in order to achieve better results. It is imperative that *no* contamination of the chemicals take place since it is likely that the result will be a roll of film which is unuseable or unprintable.

Since the rate of development is dependent upon the solution temperature, the manufacturer's specifications (generally 68°F) must be adhered to. This is important since the rate of development of each layer will change under different solution temperatures and yield a color balance in the film which is incorrect. The easiest way to maintain the recommended temperature is to place each tank in a common water bath which is maintained at 68°F. Thermostatically controlled water mixing units or an accurate thermometer serve to keep this variable constant. The temperature must be checked before the start of development.

In addition to temperature, the rate of development of each layer is affected by the agitation of the films in solution. The processing instructions usually specify exactly the amount of agitation to be used in a given interval of time. This is one of the tasks which makes color processing so tedious.

If one intends to do any great amount of color developing, a reference standard should be used to judge the acceptability or unacceptability of the process. A number of step wedges are exposed in a sensitometer using the same film type (and preferably the same film lot) as will be used to expose the scene. With fresh chemistry from a suitable processing kit, one of the step wedges is processed and becomes the "standard". The others remain unprocessed and are stored for future use when it will be desirable to compare the results of the used chemicals with the results when the chemistry was new. A fairly accurate idea of developer depletion can be seen by plotting the measured density differences between the standard wedge and the test wedge. The exact procedure for setting up such control charts is discussed in Chapter 7.

2.3.5 Color Film Storage After Processing

Color films are much more stable after processing than they are before. Nevertheless all color films (particularly negatives since they are used to produce positives) should be handled with care to avoid degradation of the color. High humidity (especially in conjunction with heat) can cause a mold to form which will leave tiny, indelible marks on the film. Storage of films in air-tight containers with a desiccant will eliminate the problem.

Films should be kept clean, dust free, and handled only by the edges. Transparent sleeves provide adequate protection from finger marks and dirt. Gloves should be worn when the films are not mounted in slide holders or sleeves. In addition to physical handling, long exposures from projection lamps will accelerate fading of the color. Moisture increases the fading rate, while chemical fumes will change the color balance and eventually ruin the dye images. Films can be cleaned by either of the following methods:

- Dust and Lint — Remove with a clean camel hair brush or soft, lint-free cloth.
- Fingermarks or Grease — Remove with commercially available film cleaners applied with a soft wad of cotton.

2.4 Uncontrollable Causes of Color Error

2.4.1 Manufacturing Tolerances

The ability of either a negative or reversal tripack emulsion to yield acceptable color reproduction and tone is dependent not only upon the care of the user, but also upon manufacturing limitations. Theoretically, all rolls of film of the same type should perform identically under identical conditions. This is, in fact, not feasible since no manufacturer can make all production runs of an emulsion coating exactly alike. Small variations from the ideal set of film specifications constitute a film tolerance which must not be exceeded. For example, Eastman Kodak only releases those batches of Ekachrome film which are correctable to the rated film speed by adjustment of the camera lens diaphragm not to exceed ½ stop. Assuming the film has been stored correctly, the speed of Ektachrome film will be within ½ stop of the published value (given on the film data sheet). Similarly, the color balance of the Ektachrome emulsion is maintained so that all the released film meets the following specification. The color balance of the released emulsion must be no greater than the color shift generated by using a Kodak CC10 Color Compensating Filter. For optimal results, however, the color balance and speed of any film should be established by trial exposures so as to account for any small variations in manufacturing tolerances, storage anomalies, and processing conditions.

2.4.2 Reciprocity Effect

All photographic emulsions are designed to be exposed for some nominal time to a specific source of light. This assures correct color balance and tone. It is not always possible, however, to follow these exposure times and often the necessary exposures are considerably longer or shorter than the manufacturer's recommendations. Beyond certain limits this causes a shift in the exposure of each layer, as well as the rated film speed and is known as reciprocity effect. The film manufacturers usually supply (for *each* emulsion) the adjustments which are required for exposures quite different from the normal exposure times. Consider Figure 11. The reciprocity law failure characteristics are similar over the range of exposures from .10 second to .001 second. Exposure times longer than .10 second cause a change in the speed of each layer. Hence, a filter over the lens would be required to produce the correct color balance. Also, the rated film speed of ASA 64 would only be valid over the exposure range of .1 to .001 seconds. An example of the reciprocity characteristics of color films as supplied by the manufacturers is as follows:

Exposure Time	Exposure Correction	Filters Required
1/1000 sec.	None	None
1/100 sec.	None	None
1/10 sec.	None	None
1 sec.	+1 Stop	CC10 Red
10 secs.	+1 ½ Stops	CC10 Red
100	+2 ½ Stops	CC10 Red

If the ASA of this film is 64 and one is using a light meter, then at an exposure of one second, the meter should be set at ASA 32 (1 stop less). The addition of the red correction filter indicates that the reciprocity law failure is least for the blue and green sensitive emulsion layers.

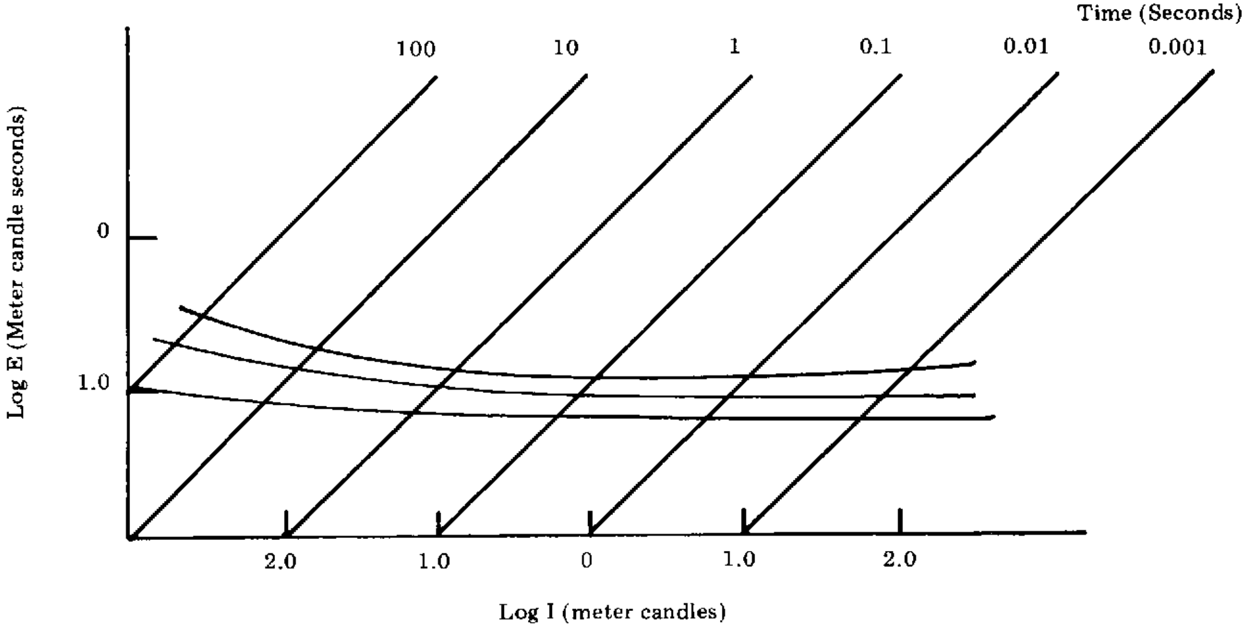


Figure 11. Reciprocity law failure in a reversal color film.

It is often more practical to send color films out to a developer to be processed than to equip a lab with the necessary controls for accurate results. Several aerial film processing centers are available and reliable results are guaranteed. The following companies offer such services and their work is quite good:

- Data Corporation, Dayton, Ohio
- Color Technique, Chicago, Illinois
- Key Color, Mineola, New York

It is also true that government agencies such as NASA, RADC, WPAFB, etc., have excellent color film processing facilities. They are, however, often backlogged and it may take some time before the work can be done.

2.5 Relationship Between Processed Color and Standard Test Panel Color

Whenever it is required to produce the best possible results using color negatives or reversal films, both exposure and processing tests should be made. Understanding corrective procedures for color emulsions is invaluable for the skillful handling of these materials. The means for determining the printing characteristics of color negative films will be considered first.

The principal causes for speed and color balance changes in the color negative are: manufacturing variations, poor storage conditions, incorrect exposing illumination, film sensitivity differences as a function of light level, and non-standard processing conditions. One or more of these causes can occur at the same time (their effect is usually additive); hence, unsatisfactory prints will be produced unless compensation is made in advance.

When evaluating the exposed color negative for printing, it is essential that determination be made of the exact exposure, as well as the specific set of printing filters to be used. A procedure has been established which consists of comparing the relative amounts of red, green, and blue light which are transmitted through a standard step wedge on the film. This standard wedge may be either: (a) placed in the scene and photographed under the same illumination conditions as the subject, or (b) sensitometrically exposed on the leading and trailing ends of the color film roll prior to camera exposure. This test target usually consists of a gray scale; Chapter 4 discusses the advantages of placing such a target in the scene.

Regardless of the exact color printing material used, each consists of three layers sensitized to a particular color light — red, green, or blue. Hence, each layer must receive the correct exposure in order to yield both satisfactory density and color balance on the reproduction. A change in the overall exposure time will affect all three dye images, while color compensating or printing filters will affect the exposure of one or two of the emulsion layers. For example, a yellow filter affects only the blue layer, while a green filter will affect both a blue and red sensitive layer. By manipulating the overall exposure, as well as the printing filters, a proper exposure on each of the three layers can be obtained. The evaluation of a color negative consists basically of a measurement of the red, green, and blue densities of the standard target negative which indicates the adjustment necessary to produce correct color reproduction.

Three step wedges will be evaluated in this analysis. They are:

- The *standard* which is exposed onto the film leader and trailer.
- The *negative* step wedge resulting from processing the color film.

- The best possible *color print* step wedge.

Measurements of color densities require the use of a color densitometer or, if the densitometer is not supplied with color filters, the use of a Kodak Wratten #70 (red) filter, a #99 (green), and a #47B (blue) will suffice. After color processing the entire roll of film, the step wedge is removed from the roll and a series of test prints are made from it. The gray scale should (in the positive) be strictly gray — no tint of red, green, or blue should be present. The best possible color print is then set aside and the following procedure is used to print the positives of the actual photography. Reference is made to the data sheet of Figure 12. Assume that the densities for the standard negative are: R = .95, G = 1.0, B = 1.20. Assume that the densities for the production negative are: R = 1.10, G = .95, B = 1.10.

- Measure the red, green, and blue densities of the midgray scale patch in the *standard negative* wedge. Reading to two places is usual. The red reading is recorded under cyan of Figure 12, the green reading is recorded under the magenta in Figure 12, while the blue density is shown under the yellow column of Figure 12.
- In the appropriate column, record the values of the printing filters used to produce the best *positive* of the step wedge.
- Add the steps 1 and 2 in Figure 12 for each column.
- Measure the red, green, and blue densities from the *negative* produced from the standard wedge. Enter these values in the appropriate columns of Figure 12.
- Subtract the values shown in Step 4 from those in Step 3 of Figure 1.2
- Add *or* subtract the amount shown in the first column of Figure 12, so that the cyan value is zero, (step 6).
- The resulting values under magenta and yellow represent the printing filters to be used. (step 7).
- To determine the correct exposure for the print, take the cyan value (step 6) shown in Figure 12, refer to Table II, and multiply the exposure used to produce the negative step wedge by the value shown in this table.

Step #	Cyan (Red Reading)	Magenta (Green Reading)	Yellow (Blue Reading)	
1	.95	1.00	1.20	Standard Wedge Density
2	+0	+ .65	+ .80	Print Filters
3	.95	1.65	2.00	Add 1 and 2
4	-1.10	- .95	-1.10	Production Negative Density
5	- .15	.70	.90	Subtract 4 from 3
6	+ .15	+ .15	+ .15	Value added or subtracted to make cyan = 0
7	0	+ .85	+ 1.05	

Printing Filters = 85M and 105Y

Figure 12. Negative evaluation table for printing positives.

Cyan Value of Step #6	+.40	2.6	Multiply Standard Exposure by this Value.
	+.30	2.0	
	+.20	1.6	
	+.10	1.25	
	+0	1	
	-.10	0.8	
	-.20	0.65	
	-.30	0.50	
	-.40	0.40	

Table II. Exposure Calculation Table

This procedure gives the correct printing filters and exposures required to produce color correct prints.

The use of test exposures is even more essential in the case of reversal materials since it is *not* possible to alter the density or color balance in the final reproduction. Positive images are produced directly so that it is essential to: (1) expose a number of step wedges onto the reversal film, (2) process them before the actual imagery, and (3) examine them for accuracy of reproduction, relative to the original step wedge. A list of possible color processing errors is shown in Table III and each step wedge processed by the reversal development kit is examined for these errors. When found, the corrective procedure indicated in Table III should be taken.

Table III. Positive color processing errors.

Appearance of Film	Possible Causes
Very dark, almost opaque	Bleach or fixer omitted.
Dark overall	Idadequate time, temperature, or agitation in First Developer. First Developer underreplenished, exhausted, or diluted.
Light Overall	Excessive time, temperature, or agitation in First Developer. First Developer overreplenished.
Overall density variation from batch to batch	Inconsistencies in time, temperature, or agitation in First Developer; or variations in First Developer replenishment rate.
Red	Color developer improperly mixed.
Bluish-magenta	Color developer diluted, exhausted, or underreplenished.

Magenta areas and streaks	Uneven or insufficient agitation in First or Color Developers.
Yellow	Film fogged by room lights during First Developer step (may show partial negative image).
Yellowish-green	Film fogged by yellow-green safelight; Color Developer overreplenished or too alkaline.
Blue specks	Chemical contamination. Do not allow metallic particles or chemical dust to come in contact with film.
Fungus or algae in processing solutions solutions or wash tanks	Can be controlled by cleaning and sterilizing processing, replenisher, and wash tanks periodically. Use a 50-micron rating (or finer) filter in the water supply system.

2.6 Summary

- Color films possess the following basic advantages: excellent resolution or registration of the color, any single lens camera is adequate for exposure of color film, results are generally good approximations of the colors in the scene, no requirement for auxiliary equipment with which to view the results, a single exposure value is valid for each of the three layers.
- Color films are limited by the following factors: fixed exposure ratio between the emulsion layers, fixed sensitivity of each layer to light of a particular color, final color on film cannot be altered to any great extent, requirement for precise exposure and processing, high cost.
- Storage of color emulsions should be at low temperatures and humidity; they should be kept away from processing chemicals which can cause them to deteriorate.
- Errors in brightness of a scene on color films, also affects the color of the subject.
- Negative color films are exposed so that both shadows and highlights fall on the straight line portion of the characteristic curve.
- Reversal color films are exposed so as to correctly reproduce the highlights of the scene.
- Color films often require the use of a correction filter because of differences in the quality of the illuminating source.
- Processing kits are recommended for developing color films and strict adherence to the manufacturer's instructions is essential.
- Solution temperature, agitation, and processing times greatly affect the appearance of images on color films.
- Storage of processed color films away from high humidity, dust, long exposures to light, and chemical fumes will maintain the stability of the color dye images.
- Negative color film evaluation consists of determining the correct exposure and printing filters which will be required to obtain satisfactory color reproduction.
- Changes in *printing exposure* alters the color balance of *all* three dye layers.
- Use of *printing filters* alters the color of only one or two of the emulsion layers.

CHAPTER 3

IMAGE COLOR MEASUREMENTS

The complete interpretation of color imagery requires that the photo interpreter be able to accurately define his visual color sensations on an extremely consistent basis. Some typical questions concerning color quality may be: "Just how red is the red image", "To what extent does it differ from another red image?", and more importantly "How much variability in the perceived red color exists between several photo interpreters?". The importance of these questions rests in the fact that what we see in an image, including its color, is our best guess as to what it is. In an effort to solve the dilemma of accurately specifying a color sensation, many color languages and systems have been devised. Only three will be presented here, but they are the most popular: the Munsell, the CIE Colorimetric, and the CIE Spectrophotometric systems of color definition.

3.1 The Munsell System

The Munsell System consists basically of specifying the *appearance* of a color by visually comparing it to a set of standard color chips or samples. These color chips are positioned in what is known as the Munsell Color Solid, shown in Figure 13. The central axis, representing the neutral or gray colors, is divided into ten equal steps with the white point at the top and the black point at the bottom. This axis specifies the degree of lightness or brightness of a color and is called VALUE in the Munsell notation. Munsell value is zero for an ideal black surface having a reflectance equal to zero; the Munsell value is ten for an ideal diffusing white surface having a reflectance equal to 100 percent.

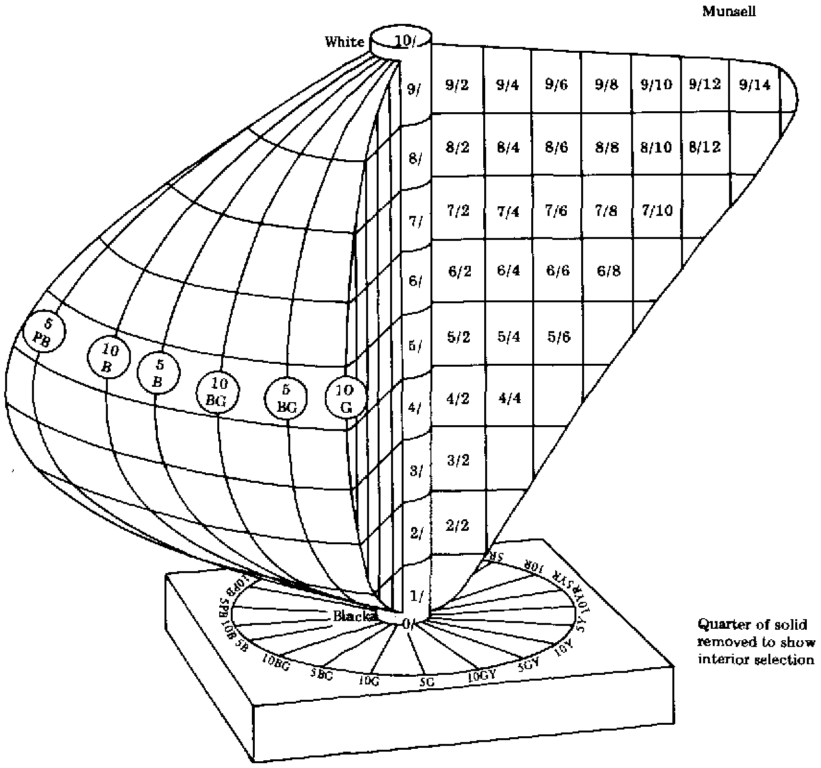


Figure 13 — Munsell Color Solid.

The Munsell System defines 100 hues of equal perceptible difference. These hues are divided into ten groups of ten hues each. The hue groups are given initials representative of the central member of the group as shown in Figure 14a. The groups are, actually, ten equally spaced vertical planes (Figures 14b) passing through the neutral or value axis and specify the major colors in the Munsell System. Ten minor hues surround each principal hue and they are numbered from one to ten. Hence, the most purplish of the red group is designated as 1R, the most yellowish of the red group as 10R, while the pure red hue is denoted as 5R, or simply R. More detailed letter abbreviations become difficult to handle so that the number-letter combinations (such as 3G) are generally used. The saturation of a color is determined by its horizontal distance from the central value axis and is known as CHROMA in the Munsell notation. The number of chroma steps depend upon the hue and value; however, each step represents equal saturation intervals.

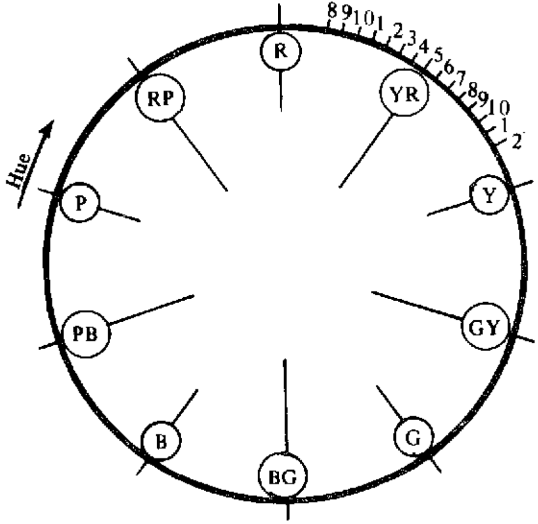


Figure 14a. Hue designations in the Munsell Color Chart.

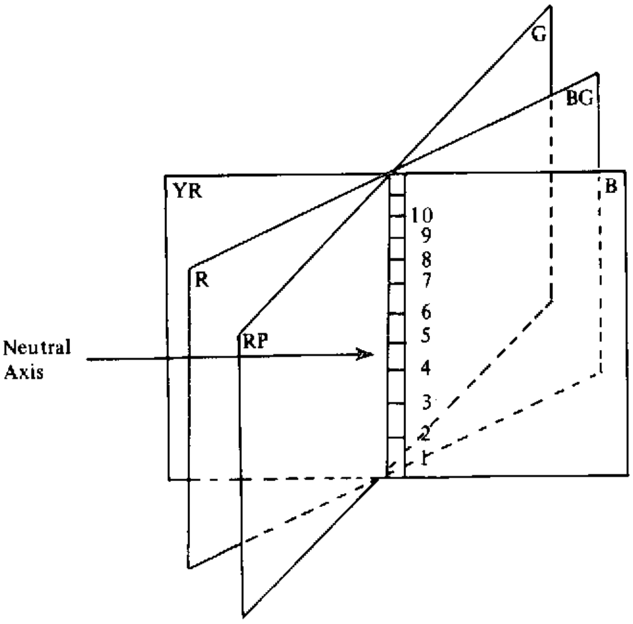


Figure 14b. Hue planes of the Munsell Color Solid.

The appearance of a color in the Munsell System may be specified in two basic ways:

- By visual description — purple, yellow-green, etc., as shown in Figure 15. The difficulty with this method is the confusion of associating the color name with the visual sensation.
- By letter and number — for example, 7R (or the 7 section in the red segment).

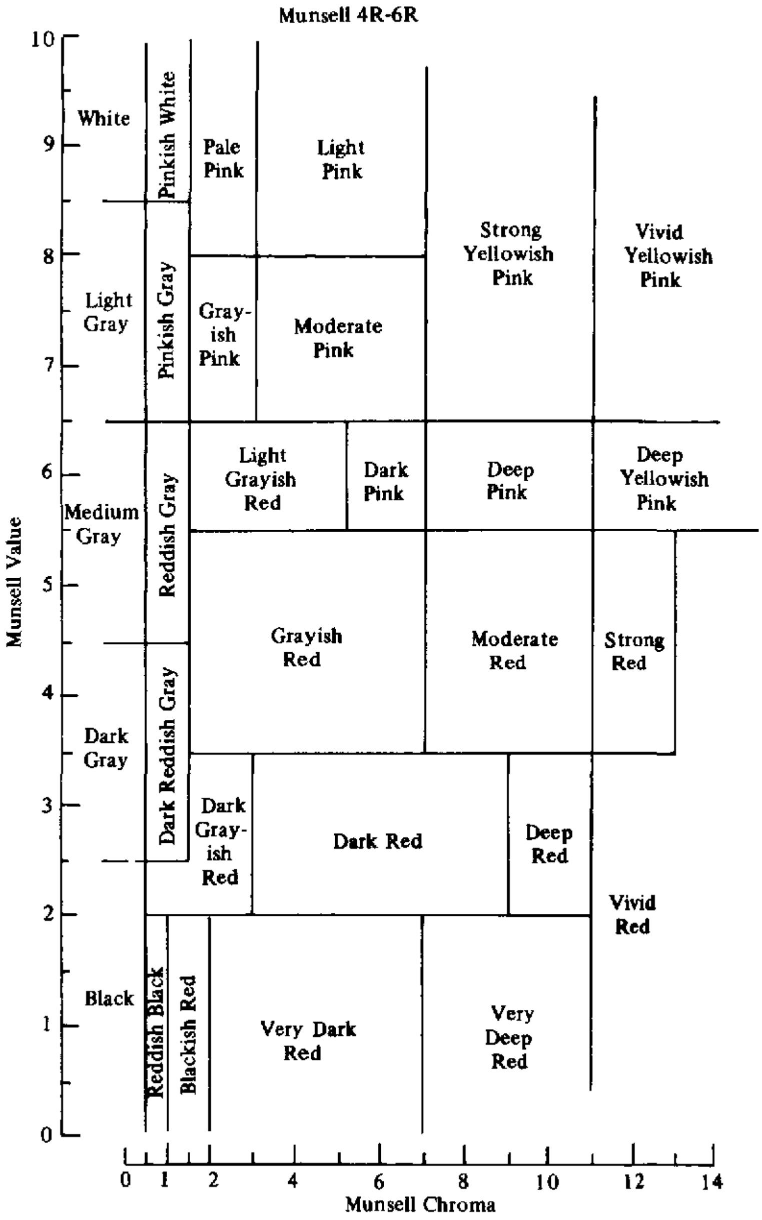


Figure 15. Color names associated with Munsell solid.

The complete Munsell description of color is written in the following way: Hue Value/Chroma. Hence, 5Y 6/5 designates a color which has a pure yellow hue, is slightly brighter than the center value, and has a chroma which is five steps from the neutral gray value of six. It should be noted that intermediate hue values are possible, such as 5.5Y 6/5. Neutrals or grays are given the letter notion

N; for example, N/5 represents a gray in the center of the value scale since there is, of course, no hue description for neutrals. The Munsell *Book of Color,* containing over 1200 chips, is so manufactured that the hue, value, and chroma spacing between the samples is intended to be visually uniform. The *Book of Color* is used to subjectively evaluate the appearance of a color, providing that average daylight (neutral or artificial) is used as the illuminant. When comparing an unknown color with the Munsell chips, the unknown must be placed adjacent to the chip and held in the same plane. If this cannot be accomplished, then rectangular paper masks of the same size are placed over both the sample and the chip. It is *essential* that the brightness or value of the mask be about the same as the sample. That is, if the unknown sample is light, the mask should be light and if the unknown is dark, the mask should be dark. Precise color comparison is not possible when the value of the mask is appreciably different from the unknown. Examples of this fact are shown in "Color: A Guide to Basic Facts and Concepts" by Burnham, Hanes and Bartleson.

The primary disadvantages to the Munsell System are threefold:

1. It employs the extremely variable human eye.
2. It is only applicable to opaque test objects.
3. It is extremely difficult to manufacture the exact required color in the chips and, indeed, it is often impossible.

3.2 CIE Colorimetric System

In 1931, the CIE System was adopted as the international standard for the specification of color. Contrary to the Munsell System, the CIE precisely defines the illuminant and viewing conditions of the sample (color) and has established a mathematical framework for the *objective* specification of color.

A set of three standard illuminants exists in the CIE system:

1. Illuminant A, which consists of a gas-filled tungsten lamp operating at a color temperature of 2854°K.
2. Illuminant B, which consists of an illuminant A lamp and a special filter to produce an approximation of noon sunlight. Its color temperature is 4870°K.
3. Illuminant C, which consists of an illuminant A lamp and a special filter to produce an approximation of daylight or a completely overcast sky. Its color temperature is 6740°K.

Let us assume that one of the CIE standard illuminants is used to view a colored object. It is apparent that the appearance of the colored object will change depending upon its size, its background color, and its proximity to other colors. Variations in the adaption of the visual mechanism of the eye can affect the color that is observed. In an effort to minimize these effects, the CIE system has precisely defined a standard manner in which colors are to be viewed:

- A circular field of view subtending a visual angle of 2 degrees.
- A completely dark background.
- For reflecting materials, the illumination angle must be 45° and the sample must be viewed normal to its surface.

3.2.1 Colorimetry

Colorimetry is defined as the technique associated with the physical measurement of a color. It was developed to fulfill the critical need for a color specification system which would be more accurate and more precise than the system of using color chips and color names. Colorimetry is not a subjective science; that is, unlike the Munsell it is generally not dependent upon an observer. Rather it is a *mathematical* description of the color perceived by the visual mechanisms of the eye, in terms of the three basic independent variables of hue, brightness, and saturation.

It would seem natural, therefore, that these three attributes of color could be envisioned by and represented in a three-dimensional diagram. The CIE system established a color solid shaped like a rounded triangle standing on its apex, as shown in Figure 16. The brightness is represented by the vertical axis with the black point at the bottom of the solid and the white point at the top. The hues are located around the periphery of the triangle, while the line of desaturation exists between any hue point on the periphery and the neutrals or vertical axis.

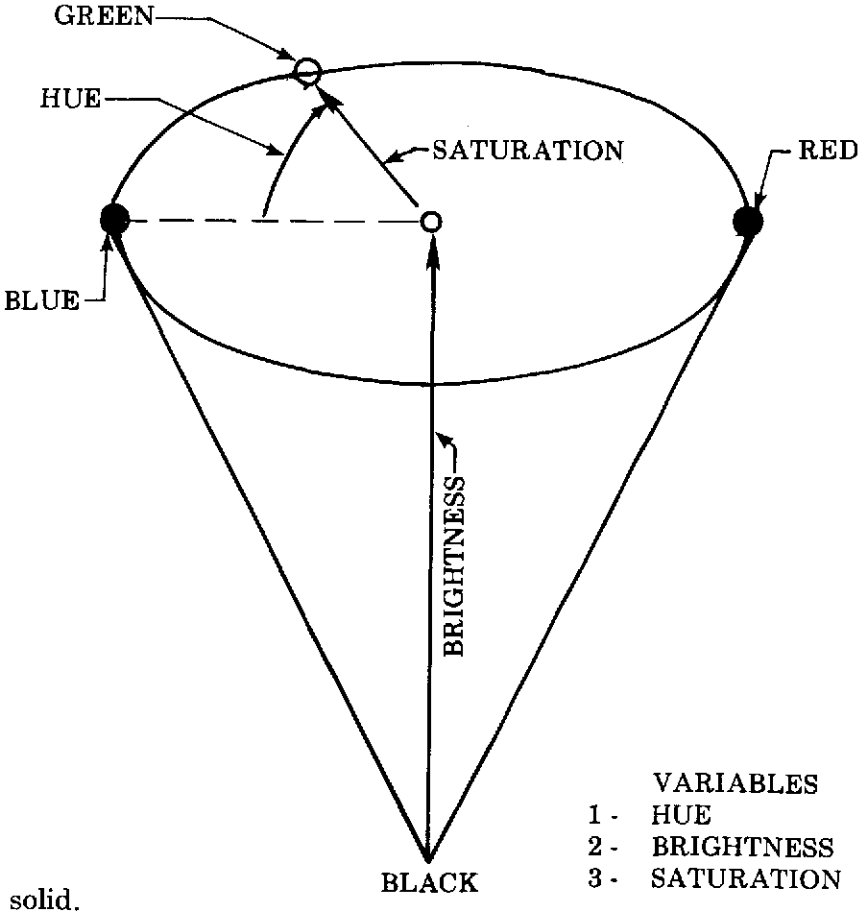


Figure 16. CIE color solid.

If one takes a horizontal slice through the color solid of Figure 16 at any brightness level, then Figure 17 is produced and is commonly called a chromaticity diagram. Referring to Figure 17, the hue is given around the edge of the chromaticity diagram in terms of dominant wavelength. Notice that the wavelength of the deepest purple is 380 nm at the lower left of the figure. Following the periphery of the pure colors towards green to yellow and red, the highest dominant wavelength for the visible spectrum is 700 nm.

The question which arises at this point is, just what do the color coordinates (x, y) shown in figure 17 represent and how do they relate to the color sensation we perceive. The color coordinates (or chromaticity coordinates) *uniquely* describe a particular visual stimulus in terms of hue, brightness,

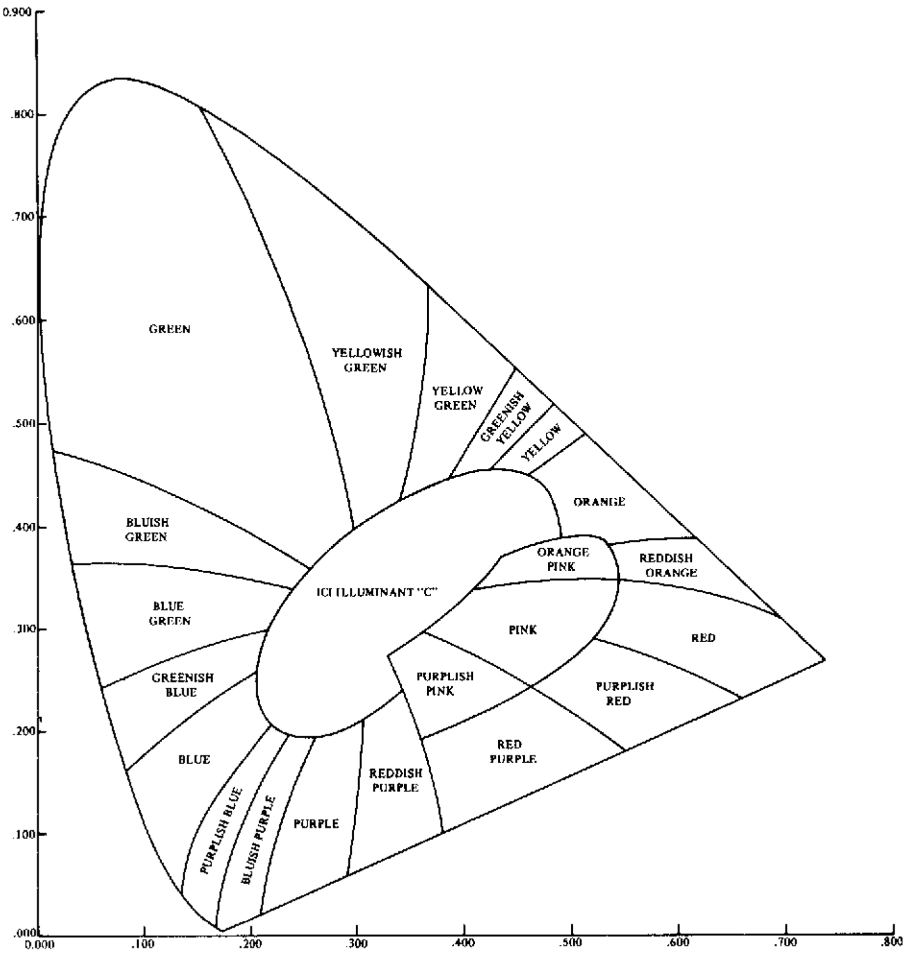


Figure 17. CIE chromaticity diagram.

and saturation. Consider Figure 18 which is a chromaticity diagram for a brightness level of 10 and containing a color A having coordinates (.15, .7) described basically as a greenish hue. More specifically, by drawing a line, as shown in Figue 18, between (.15, .7) and the white point (.33, .33) and by extending that line through the edge of the chromaticity diagram, the dominant wavelength of the color is found to be 520 nm.

Also, we shall now measure:

— the distance between the white point and the pure hue (BW)

— the distance between the color and the pure hue (AB). If AB is one unit long, then BW measures about 3.5 units long. Desaturation of the color is computed directly from these two measurements as follows:

$$\text{Desaturation} = \frac{AB}{BW} = \frac{1}{3.5} = .285$$

Since desaturation is the opposite of saturation, the latter may be written the following way:

$$\%\ \text{Saturation} = 100\% - (\%\ \text{Desaturation})$$

Hence, in the example above, the color is 28.5 percent desaturated *or* it is 71.5 percent saturated *or* it

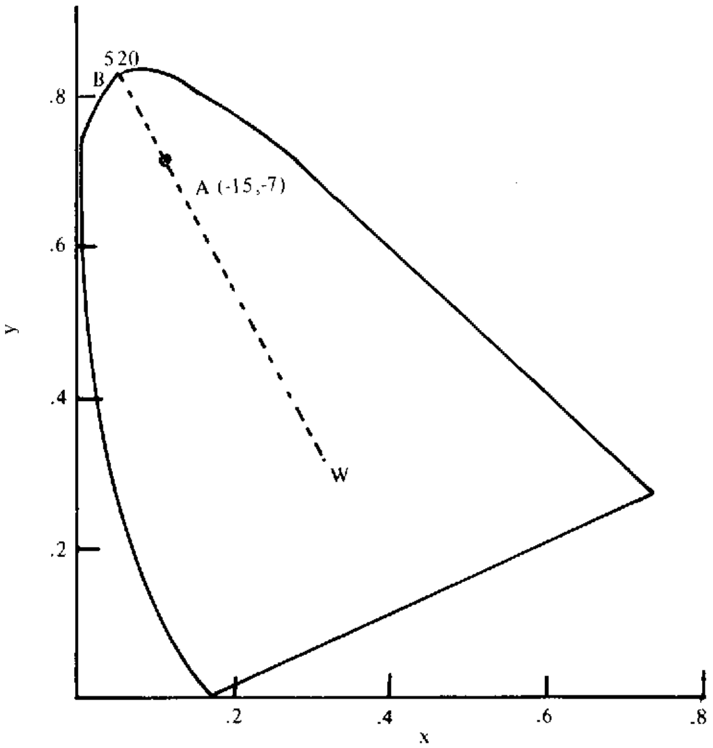


Figure 18. Calculation of desaturation from chromaticity diagram.

is 71.5 percent pure. Summarizing now what has been determined about the chromaticity coordinates (.15, .7) plotted in Figure 18.

- the general color is green
- the dominant wavelength or hue is 520 nm
- the saturation is 71.5 percent
- its brightness is 100 percent

Note that in the above case, not only were the chromaticity coordinates given, but the brightness level of 100 percent were defined. The correct way of specifying this set of color coordinates as well as the brightness level is (x, y, Y), where Y is the percent brightness of the color.

The versatility of the chromaticity diagram also allows for a simple determination of the resultant color produced by an additive combination of two lights. Consider Figure 19. The primary lights are represented by the corners of the inscribed triangle. The choice of primaries for additive viewing should fulfill two conditions:

— The area within the triangle should be as large as possible, since only colors located *within* it may be additively produced by mixture of the primaries blue, green and red.

— The triangle should be shifted towards the yellow region since pure yellow exists in nature, while pure cyan does not.

The colors produced by the addition of the red and green primaries of Figure 19 will *all* lie along the line GR, their exact positions being a function of the amounts of each primary mixed to produce the color. The additive combinations of the red and blue primaries will lie along the line BR and the additive combinations of the green and blue primaries will produce colors along the line BG. It can also be seen from Figure 19 that the additive combination of one primary and its complimentary color will produce hues which lie along the line passing through the white or neutral point. For example, adding blue and yellow light will produce colors along the line BWY.

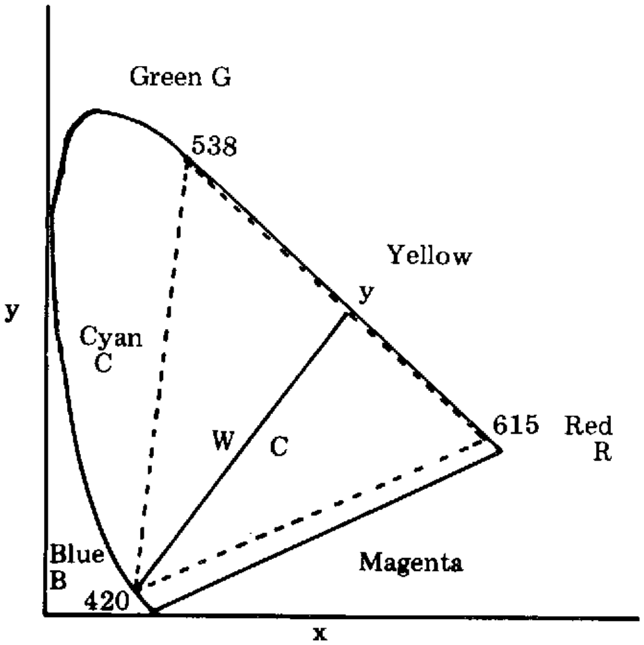


Figure 19. CIE diagram showing primaries and the color triangle produced by them.

To understand how the chromaticity coordinates (x, y, Y) are generated, it is necessary to explain one of the most fundamental concepts of color: any sample color can, in general, be matched by the mixture of at least three primary colors. This concept will now be explained.

3.2.2 Color Mixture

The Three Primary Method of color mixing consists of matching a sample color by the combination or addition of three primary colors nominally described as red, green, and blue. Consider a set of four projectors arranged as in Figure 20. Notice that the first projector contains a blue filter, the second a green filter, and the third a red filter. Projector #4 contains no filter and *each* unit is equipped with an iris diaphragm to control the amount of each primary being projected onto the screen.

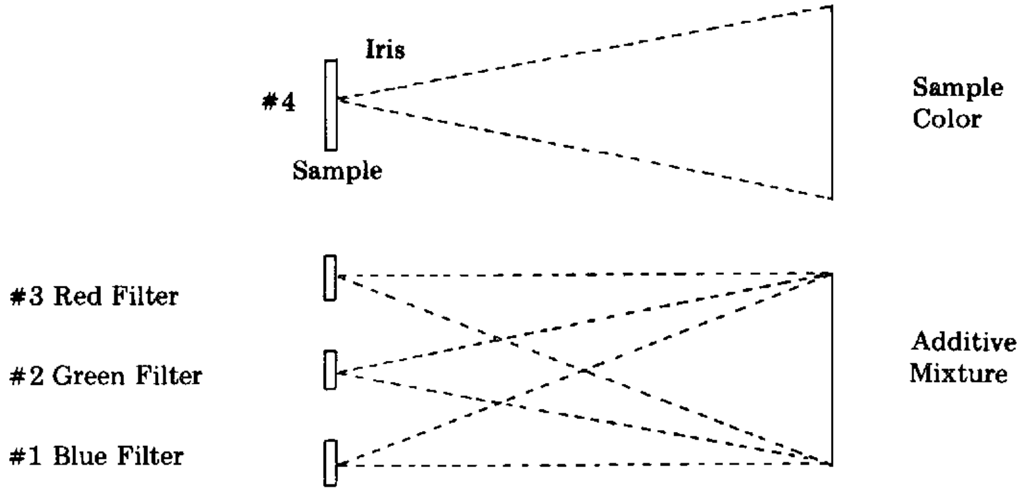


Figure 20. Three Primary Method of color matching.

Let us initially ignore projector #4 and examine what happens when we optically mix different amounts of the primary colors. By turning off the blue light and altering the proportions of red and green, a series of colors is produced on the screen ranging from pure red to pure green and passing through orange-red, orange, yellow, and yellow-green. Similarly, by turning off the red light and projecting the blue and green, a series of colors is produced ranging from pure green to pure blue and passing through cyan (turquoise). Again, by turning off the green light and projecting only varying amounts of blue and red, it is possible to produce all colors ranging from pure blue to pure red and passing through magenta (red-blue). If *equal* amounts of the red, green, and blue primaries are projected, the resultant color is white or neutral gray. When *unequal* amounts of the three primaries are projected, the color combination is something other than white or neutral gray.

If a sample color, H, is shown on the screen through projector #4, there will exist some combination of the amounts of the primary colors from projectors, 1, 2, and 3 which will match the sample color. Hence, it is said that the color, H, is equal to, or is produced by, optically mixing together X units of the red primary, Y units of the green primary, and Z units of the blue primary. Writing this mathematically.

$$H = (X)r + (Y)g + (Z)b$$

This color may not be *specified* in terms of X, Y, Z; that is, in terms of the amounts of the three primaries necessary to create a match to the sample color. X, Y, and Z are called TRISTIMULUS values.

Assume now that the color, H, consists of 86 units of red, 52 units of green, and 8 units of blue. Written mathematically,

$$H = 86r + 52g + 8b$$

Although we might be tempted to say that this color is reddish (since there are more units of red than green or blue), it is easier to analyze the color in terms of *percentage* of red, the *percentage* of green, and the *percentage* of blue than analyze it in terms of number units.

$$\text{Proportion Red} = \frac{\text{\#Red Units}}{\text{Total \#Units}} = \frac{86}{146} = .589$$

$$\text{Proportion Green} = \frac{\text{\#Green Units}}{\text{Total \#Units}} = \frac{52}{146} = .356$$

$$\text{Proportion Blue} = \frac{\text{\#Blue Units}}{\text{Total \#Units}} = \frac{8}{146} = .055$$

Therefore, the color H, is 58.9 percent red, 35.6 percent green, and 5.5 percent blue. The proportions of the primaries as defined above are now rewritten using the tri-stimulus notation:

$$\text{Proportion Red} = \frac{X}{X+Y+Z} = x$$

$$\text{Proportion Green} = \frac{Y}{X+Y+Z} = y$$

$$\text{Proportion Blue} = \frac{Z}{X+Y+Z} = z$$

x, y, z are called TRICHROMATIC coefficients. Note that x and y are the chromaticity coordinates that were discussed previously and the tristimulus value of Y defines the brightness level. Hence the color, H, is uniquely defined as (x, y, Y) = (.589, .356, 52). The question may arise as to why one specifices this color as (x, y, Y) and not as (x, y, z, Y). Since x, y, and z are proportions, they will always add up to the number 1.00; therefore, if x and y are known, then z is also known:

$$z = 1 - x - y$$

In order to examine the effects of the tristimulus values (X, Y, Z) and the trichromatic or chromaticity coordinates (x, y, Y) in terms of hue, brightness, and saturation of a color, consider the sets of tristimulus values in Table IV.

Tristimulus Value	Case # 1	Case #2	Case # 3	Case # 4
X	40	30	50	20
Y	80	60	90	80
Z	20	15	30	20

Table IV

- Case #1: Represents an arbitrary set of tristimulus values.
- Case # 2: Each tristimulus value of case # 1 is reduced 25 percent.
- Case # 3: Each tristimulus value of case #1 is increased by 10 units.
- Case # 4: The X tristimulus value decreased from case # 1; Y,Z values identical with case # 1.

Using the Equation 3.1 for x and y given previously, the trichromatic coefficients for each of the above cases are now computed:

Case # 1

$$x = \frac{X}{X+Y+Z} = \frac{40}{140} = .285$$

$$y = \frac{Y}{X+Y+Z} = \frac{80}{140} = .571$$

$$y = y = 80$$

Case # 2

$$x = \frac{X}{X+Y+Z} = \frac{30}{105} = .285$$

$$y = \frac{Y}{X+Y+Z} = \frac{60}{105} = .571$$

$$y = y = 60$$

Case # 3
$$x = \frac{X}{X+Y+Z} = \frac{50}{170} = .294$$

$$y = \frac{Y}{X+Y+Z} = \frac{90}{170} = .529$$

$$y = Y = 90$$

Case # 4
$$x = \frac{X}{X+Y+Z} = \frac{20}{120} = .166$$

$$y = \frac{Y}{X+Y+Z} = \frac{80}{120} = .666$$

$$y = Y = 80$$

Plotting these four sets of chromaticity coordinates in Figure 21 and summarizing the results, we find:

	Case # 1	Case # 2	Case # 3	Case # 4
x	.285	.285	.294	.166
y	.571	.571	.529	.666
Y	80%	60%	90%	80%
Dom. λ	543 nm	545 nm	545 nm	520 nm
Saturation	60%	60%	50%	70%

Table V

Examination of these results leads to the following conclusions:

1. As long as the *ratio* between the tristimulus values (X,Y,Z) remains the same, both hue and saturation will be constant; only the brightness of the color is altered (see Case #1 and Case #2.)
2. Adding an *equal* amount of extra light units to each tristimulus value will desaturate the color and make the image brighter; the hue, or dominant wavelength, remains the same (see Case # 1 and Case # 3). Since equal amounts of (X, Y, Z) produce white, then it may be said that this is equivalent to adding white light to the color in Case # 1 or desaturating it; brightness is naturally increased by addition of more units.
3. The hue, or dominant wavelength, is only changed by altering the *proportions* of X,Y,Z (see Case # 1 and Case # 4).

Summarizing: The Three Primary Method of colorimetry consists of matching any sample color by the mixing of three primary colors; nominally, red, green, and blue. In order to successfully match

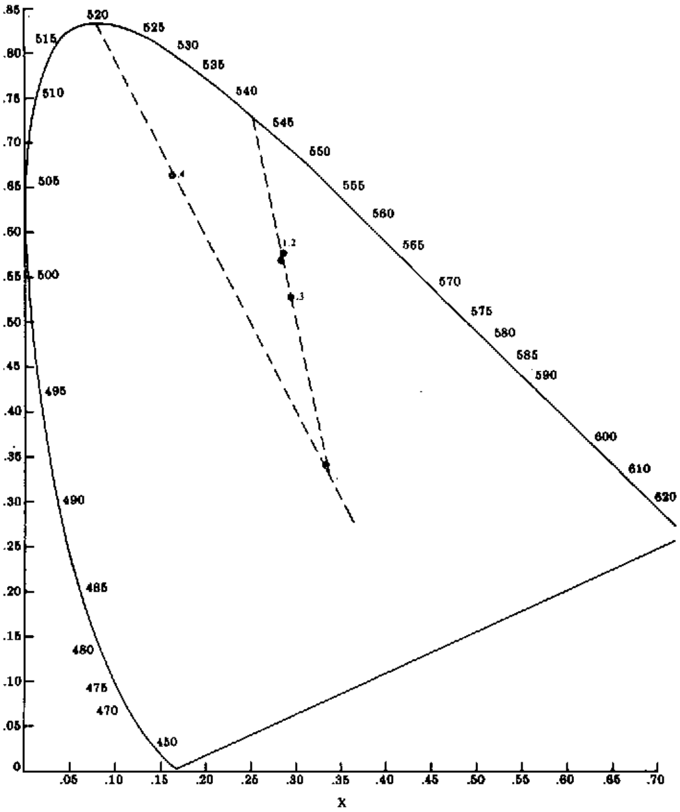


Figure 21. Chromaticity coordinates associated with the data of Table V.

any sample, the following two conditions are necessary:

- That none of the primaries may be matched by any combination of the other two; that is, each primary is unique.
- That the brightness or luminance of each primary be continuously variable. That is, each primary may be added, to a greater or lesser extent, to create a match to the sample color.

When a visual match has been made to the sample, the *amounts* of each primary required for that match are measured and they become the *specification* of the sample. *Chromaticity* coordinates, on the other hand, are specified as the *proportion* of the primaries in the matched color (not the amount). Most sample colors can be matched by the mixture of the three primaries: red, green, and blue. That is,. a color, H, may be specified as:

H = r units of red + g units of green + b units of blue
or:
H – r(R) + g(G) + b(B)

Further analysis has shown, however, that some colors cannot be suitably matched in this fashion. That is, there appears to be (to the eye) an excess of one primary in the matching field. Hence, the sample color and the mixed primaries can only be made to match by *adding some primary to the sample color.* For example,

(1) Non-match: H = r(R) + g(G)
(2) Match: H + b(B) = r(R) + g(G)

In this illustration, the color, H, (in situation 1) is not matched to r units of red and g units of green; there appears to be an excess of blue in the primary field. By adding b units of blue to the sample field (as in 2), however, a color match is made. The equation (2) above may be written:

H = r(R) + g (G) – b(B)

The amount of primaries in a mixture, then, may exist as either positive or negative quantities. Using this Three Primary Method of color matching, the CIE in 1931 selected a set of three primary colors (peaking at about 436 nm, 546 nm, and 700 nm) to match very narrow color bands throughout the visible spectrum. The amounts of red, green, and blue primaries required to create these matches were then plotted and are shown below in Figure 22.

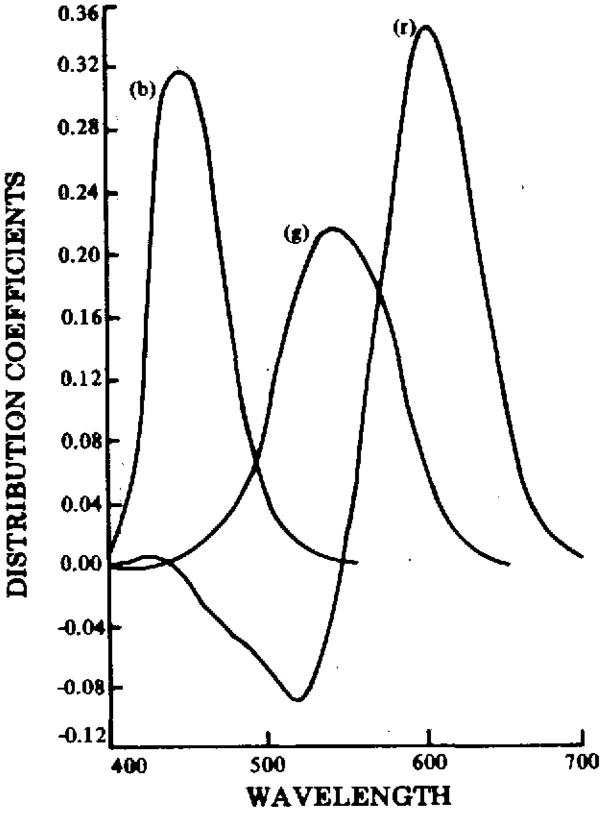


Figure 22. Standard observer color mixture curve.

The pure color at 470 nm, for example, was matched by 16 units of blue, 3 units of green, and minus 4 units of red, or:

$$H_{470} = -4R + 3G + 16B$$

These curves shown in Figure 22 are called *color mixture curves* and indicate *exactly* the amounts of each specified primary necessary to match the sample (naturally for a standard observer). It would be ideal, therefore, to use filters for all color matching problems which are identical to the curves of Figure 22. However, because they possess negative values they would be impossible to manufacture. Although such filters are non-existent, it is feasible to generate a second set of filters which are a linear, homogeneous combination of the curves in Figure 22. Such a set could possess *no* negative values and one of these new color-mixture curves could be made identical with the luminosity function of the eye. That is, the human eye possesses a different sensitivity depending upon the region of the spectrum under observation, as shown in Figure 23.

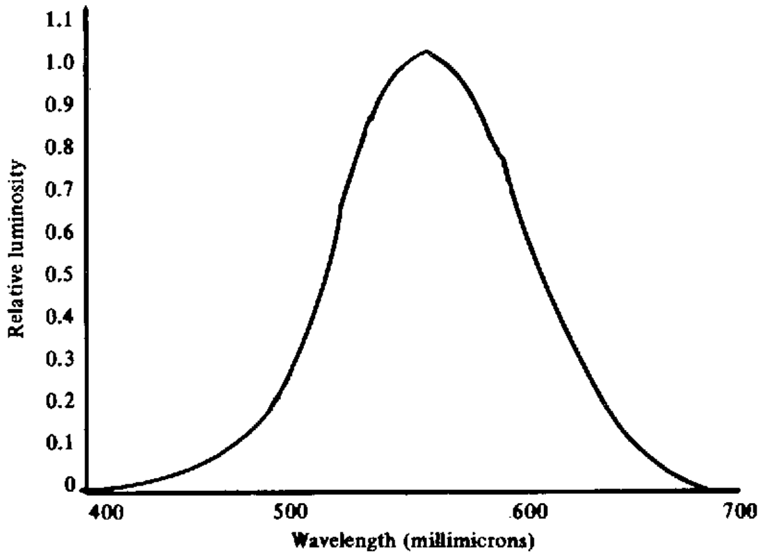


Figure 23. Luminosity function of the human eye.

Notice that the eye is most sensitive at 555 nm and possesses no sensitivity to light below 400 nm or above 700 nm. Using this luminosity function as the green primary will yield two results:

- The amount of green in the sample.
- The brightness of the sample.

Using the transformation procedure established in the next section, a new set of CIE color mixture curves, as shown in Figure 24, have been generated.

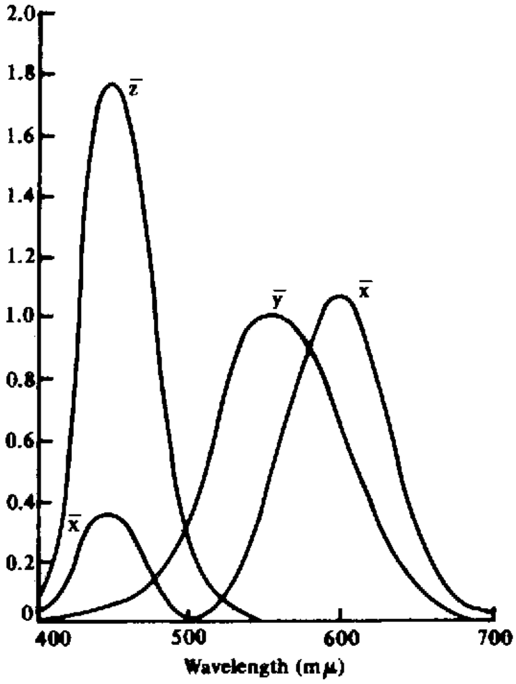


Figure 24. CIE tri-stimulus values, x, y, and z for the spectral colors.

Conversely, these color mixture curves (or the amounts of these primaries required for color matching the sample) may be transformed back into the "impossible to manufacture, but theoretically perfect" primaries of Figure 22.

3.2.3 Transformation of Primaries

In the previous section it was emphasized that the basic condition which any set of primaries must fulfill is that none of the primary colors may be matched by the mixture of the other two. If there exist two sets of such primaries, then *each* of the components of one set may be matched by an additive mixture of the second set. For example, consider two groups of primary colors as follows:

Set # 1	Set # 2
R	L
G	M
B	N

The color of primary R may be matched using a mixture of L, M, and N:
[R]

$$R = a_1 L + a_2 M + a_3 N$$

where a_1, a_2, and a_3 are the amounts of primaries L, M, and N required to match the color of R. Similarly,

$$G = a_4 L + a_5 M + a_6 N$$

and

$$B = a_7 L + a_8 M + a_9 N$$

Writing these together:

$$R = a_1 L + a_2 M + a_3 N$$

$$G = a_4 L + a_5 M + a_6 N$$

$$B = a_7 L + a_8 M + a_9 N$$

These sets of equations are known as transformation equations and the sets of a's are transformation coefficients. The above example shows the relationship between primary colors. A similar relationship exists between the *tri-stimulus* values of a color (using the primaries R, G, B) and the *tri-stimulus* values of the same color using the second set of primaries (L, M, N).

The principal reason for transformations between primary systems lies in the fact that one may wish to compare the measured color of an object using one colorimeter against the measured color using another unit. Also, one may not have access to a colorimeter; in such a case, another instrument (say, a color densitometer) can take the place of a costly colorimeter which may not be frequently used. Thirdly, most colorimeters have apertures ranging anywhere from .250 to .500 inches in diameter. One may wish to measure the tri-stimulus coordinates of an object which is much smaller than this range so that the use of a densitometer (with an aperture of 1 mm) becomes the only practical way to solve the problem.

3.2.4 Transformation of Tri-Stimulus and Tri-Chromatic Values

In order to successfully measure the tri-stimulus values of unknown colors in one instrument and convert those to another set of tri-stimulus values associated with a second instrument, two tasks must be performed:

- Three pieces of filter glass (say, red, green and blue) are analyzed on a reliable colorimeter and their tri-stimulus values measured.
- The same pieces of glass are measured for their new tri-stimulus coordinates on the second instrument (for example, a color densitometer).

To help solve the first task, the National Bureau of Standards will, for a small fee, measure the CIE tri-stimulus values of the sample glasses. Also, the manufacturers of colorimeters are often willing to demonstrate their equipment and will measure a few samples free of charge.

Now, suppose the sample glasses have associated with them the following CIE tri-stimulus values:

Red filter	X_1, Y_1, Z_1
Green filter	X_2, Y_2, Z_2
Blue filter	X_3, Y_3, Z_3

and in the second instrument (assume it's a color densitometer), the tri-stimulus values are:

Red filter	R_1, G_1, B_1
Green filter	R_2, G_2, B_2
Blue filter	R_3, G_3, B_3

Providing that the condition given at the beginning of Section 3.2.3 is fulfilled, this second set of values times some set of transformation coefficients (T) will yield the CIE tri-stimulus values. In matrix notation:

$$\begin{bmatrix} R_1 & G_1 & B_1 \\ R_2 & G_2 & B_2 \\ R_3 & G_3 & B_3 \end{bmatrix} = \begin{bmatrix} a_1 & a_2 & a_3 \\ a_4 & a_5 & a_6 \\ a_7 & a_8 & a_9 \end{bmatrix} \bullet \begin{bmatrix} X_1 & Y_1 & Z_1 \\ X_2 & Y_2 & Z_2 \\ X_3 & Y_3 & Z_3 \end{bmatrix}$$

or $$[R] = [T] \cdot [X]$$ Equation 3-2

Solving for [T]:

$$[X]^{-1} \cdot [R] = [T]$$ Equation 3-3

Equation 3-3 represents the transformation matrix [T] from the R, G, B system of tri-stimulus values of the CIE X, Y, Z tri-stimulus sytem.

Solving for [X] in equation 3-2 yields:

$$[X] = [R] \cdot [T]^{-1}$$ Equation 3-4

Substituting any set of tri-stimulus values R, G, B into equation 3-4, together with the inverse of matrix T in equation 3-3, will yield *directly* the X, Y, and Z values of the color.

The manipulation of the matrices [R], [T], and [X] is a difficult and tedious task, at best, so that the use of a small time-sharing terminal, on line to a computer, is definitely the most economic way to solve for [T] (T inverse). The following program "TRANS" shown in Figure 25 was written in basic language for a G-E time-sharing system. Some modifications may be required to assure compatibility with other computer systems.

This simple program performs the entire task, including both the evaluation of the inverse transformation matrix, as well as the calculation of the CIE chromaticity coordinates. If one wished to evaluate only $[T]^{-1}$ then the following steps should be eliminated: 8, 12, 45, 50, 55, and 100 to 200. Also, line number 52 should read MAT PRINT G.

3.2.5 Colorimeters

The instrument which is employed to directly measure the tri-stimulus coordinates (X,Y,Z) of a color is known as a colorimeter of which there are two basic types: visual and photoelectric. Most colorimeters are designed improvements over the four projector system which was shown in Figure 20 and discussed in Section 3.2.2.

Visual tri-stimulus colorimeters are optical devices in which an unknown color fills one-half of a field of view and a mixture of three primary colors fills the second half. This second half is known as the comparison field and the operator has control over the amounts of the three primaries in the comparison field. The operator looks at these two fields and adjusts the color of the comparison field until it matches the unknown color. This recorded adjustment then becomes a specification for the sample color. The purpose of visual colorimeters is to obtain a three-number specification of the sample color as simply as possible. These three numbers will then be converted into the tri-stimulus coordinates X, Y, and Z or tri-chromatic coefficients x, y, Y.

It should be noted that color specifications, in terms of tri-stimulus values, are a function of three basic variables:

- The transmission of the measured sample.
- The quality of the illuminating source.
- The sensitivity of the human eye which performs the matching task.

Visual colorimeters which employ the human eye as the sensing mechanism contain all the components necessary to fulfill the mathematical definition of tri-stimulus value.

Program Name — TRANS (Transformation of Chromaticity Coordinates)

```
Line #     Statement

   1    REMARK Program "TRANS" calculates chromaticity
   2    REMARK coordinates x, y, z from R, G, B
   3    REMARK percent transmission values from densitometer
   4    REMARK input data "Matrix C"; output data
   5    REMARK "Matrix F"
   6    DIM A (3, 3)
   7    DIM B (3, 3)
   8    DIM C (1, 3)
   9    DIM D (3, 3)
  10    DIM E (3, 3)
  11    DIM G (3, 3)
  12    DIM F (1, 3)
  15    MAT READ A
  20    MAT READ B
  30    MAT D = INV(B)
  35    MAT E = D*A
  40    MAT G = INV(E)
  45    MAT READ C
  50    MAT F = C*G
  52    MAT PRINT C, F
  55    GO TO 45
  70    DATA
  72    DATA
  74    DATA
  76    DATA
  78    DATA
  80    DATA
 100    DATA
   .     .
   .     .           Transmission values of
   .     .           colors to be evaluated.
   .     .
 200    DATA
 999    END
```

Symbol Definition

Mat A Percent R, G, B transmission values for three sample glasses

$$\begin{matrix} R_1 & G_1 & B_1 \\ R_2 & G_2 & B_2 \\ R_3 & G_3 & B_3 \end{matrix}$$

Note: These values are percentages and the sum of all the rows must equal 1.00.

Program TRANS Continued

Symbol	Definition
Mat B	x, y, z CIE chromaticity coordinates for sample glasses $\begin{matrix} x_1 & y_1 & z_1 \\ x_2 & y_2 & z_2 \\ x_3 & y_3 & z_3 \end{matrix}$
Mat F	x, y, z CIE coordinates for color to be evaluated
Mat D	Inverse of matrix B, $[B]^{-1}$
Mat E	Transformation matrix
Mat G	Inverse of transformation matrix
Mat C	R, G, B transmission values of color to be evaluated

$$X = \kappa \int R_\lambda H_\lambda \bar{x} \Delta \lambda$$

$$Y = \kappa \int R_\lambda H_\lambda \bar{y} \Delta \lambda$$

$$Z = \kappa \int R_\lambda H_\lambda \bar{z} \Delta \lambda$$

Note: These equations will be discussed further in Section 3.3.1.

That is, the object *transmits* or reflects R_λ, is *illuminated* by H_λ, and is *viewed* by the eye or by the x, y, and z visual sensitivity distributions. In photo-electric instruments, however, the object still transmits or reflects R_λ, is still illuminated by H_λ, but the human eye is no longer the sensor, so x, y, and z in the above equations are missing. This condition results in the requirement that the three photo detectors (one for the red, one for the green, and one for blue) MUST possess sensitivities which are very close to the x, y, z. Providing this condition is fulfilled, the detectors will accurately take the place of the human eye and the three readings obtained for any sample (the amounts of the three primaries required for a color match) will then be proportional to the tri-stimulus values of that sample. In practice, however, it is extremely difficult to effect an exact match of photocell sensitivity to the x, y, and z distribution curves. Good approximations have been made by employing auxiliary filters in front of the photocells. Figure 26 shows the accuracy to which the filter-photocell responses match the CIE curves x, y, z.

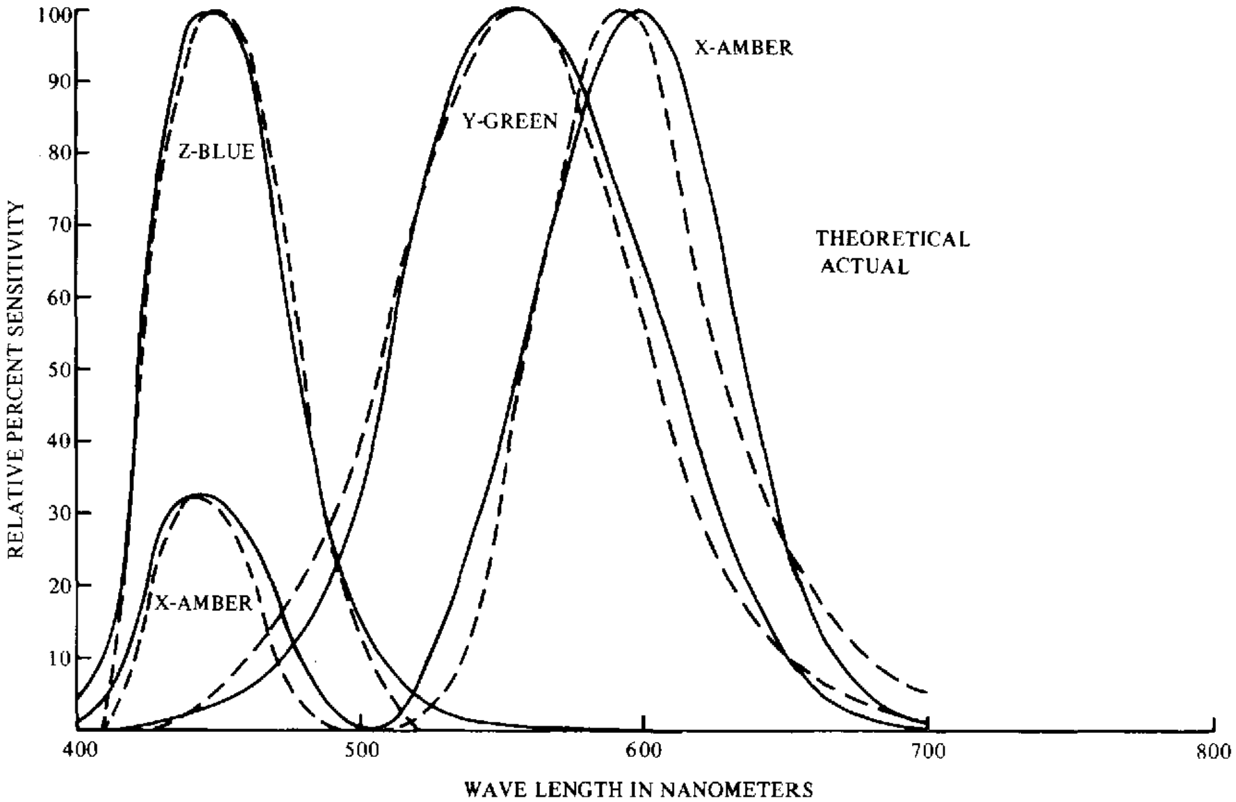


Figure 26 — Comparison of Tristimulus Curves

An example of a visual colorimeter is the Lovibond Tintometer which operates on the principle of subtractive color. This unit employs a set of magenta, yellow, and cyan glass slides as the subtractive primaries. Each set of glass slides ranges from a very light shade of the primary to a heavily saturated color. Each slide is assigned a number (the palest colors being number 1) so that any number slide may be reproduced by the addition of two or more slides whose sum equals that number. For example,

Cyan # 9 = Cyan # 4 + Cyan # 3 + Cyan # 2 = Cyan # 6 + Cyan # 3
Yellow # 4 = Yellow # 3 + Yellow # 1

The sample to be matched is placed in one-half of a four degree (4°) field of view, while the second half, illuminated by white light, has provision for insertion of the color slides. The tintometer comes equipped with a conversion graph which transforms the Lovibond measurements into CIE trichromatic coefficients, x and y. Tables are provided for measurement of the luminance or brightness Y which, when coupled with x, y, yields the complete specifications of the sample color. The primary disadvantage of this instrument is that the color matching can only be performed in *discrete* steps.

The Model XL-10 Gardner digital colorimeter is a photo-electric colorimeter for measuring color on several tri-stimulus scales, including the (CIE), the (R_d, a, b) or (L, a, b). The CIE scale permits the instrument to be used as a direct reading colorimeter in terms of x, y and z tri-chromatic values for color, while the (R_d, a, b) and (L, a, b) scales permit direct readings for color differences.

The unit incorporates all solid-state components for greater reliability and stability. This colorimeter may also be purchased with an attachment for measuring the transmission of such samples as plastic films, liquids, glass, or other translucent (transparent) materials. The unit provides for BCD output (Binary Coded Decimal). This, in general, is a means of transmitting digital data to peripheral hardware such as a printer, digital comparator, etc. A coupler or translator accepts the BCD input and converts this input to a different code which, in turn, is compatible with other hardware devices. It is possible by use of digi-switches to include in the format a sample identification. These digi-switches set up four numbers for sample identification as part of the output format. A printer is also available to write out on paper tape the data being displayed on the panel meter of the Gardner instrument. The approximate price of this colorimeter is $6,000 with the transmission attachment, BCD output, and printer.

The IDL color analysis computer system is designed for analyzing the color difference between a sample and a control standard. It describes the direction of the color difference in visually understandable terms of hue (dominant wavelength), saturation (purity), and lightness (luminance). It also analyzes the magnitude of the color difference in terms of Mac Adam units which are widely recognized as agreeing with the human eye's estimates of the size of color differences. The color analysis display computer (CADC) and a chromaticity display computer (CDC), together with a color measuring instrument, comprise the color analysis system. The measuring instrument can be almost any tristimulus colorimeter or any spectro-photometer that is equipped with a tri-stimulus integrator. Measurement information from a colorimeter is analyzed directly without the need for complex computations or charts. It takes only minutes to analyze the color difference between a sample and the standard, yielding a repeatable numerical value for each color difference. The system permits the establishment of consistent, repeatable procedures for inspection and approval of color differences from shift to shift and day to day. In production applications where the colorist must maintain the color within tolerance, the Color Analysis Computer System will provide the direction of color difference to aid the colorist in keeping the process within tolerance.

One of the newest instruments for measuring light source emissions is called TRIRAD, an automatic tri-stimulus colorimeter-radiometer, manufactured by Kollmorgan.

TRIRAD digitally displays the CIE chromaticity coordinates (x, y) after a scan and compute cycle of only 20 seconds. Additionally, it will display illuminance (Y), on a continuous basis if desired, in terms of lumens/square feet, or in the case of a CRT, when the sensor is placed against the face of the tube, illuminance (Y) is displayed in foot-lamberts.

TRIRAD is designed for rapid, precise, colorimetric evaluation of luminous emitters such as fluorescent tubes, electroluminescent sources, cathode ray tubes, color television picture tubes, and all types of lamp or lamp/filter combinations. The "signature" feature of TRIRAD, whereby close agreement to the CIE standard observer response curve is achieved, is accomplished through the use of a combination of a specially selected high sensitivity photomultiplier and individually shaped tri-stimulus filters.

3.3 CIE Spectrophotometric System of Color Specification

In previous sections, we saw that the color of an object could be specified in terms of a color name or simple visual specifications such as those associated with the Muncell System. Describing the same visual sensation in terms of the hue, brightness, and saturation parameters the CIE colorimetric system was shown to be an even more accurate color designator. However, both the Muncell and the CIE colorimetric system are concerned solely with the visual specification of a color. No attempt has yet been made to describe the spectral distribution of the color. It is this distribution which, when viewed by a standard observer, yields the visual sensations described by the Muncell and CIE Systems.

The science associated with analyzing a color into its component spectral parts and measuring the energy in each part is known as spectrophotometry. More specifically, spectrophotometry measures an object's radiant energy which enters the eye in various spectral regions.

With the exception of pure spectral lines (from the sun, for example) very few objects possess a color which has a single wavelength associated with it. For example, a theoretically perfect or pure spectral orange might be plotted as shown in Figure 27, with a dominant wavelength at 610 nm.

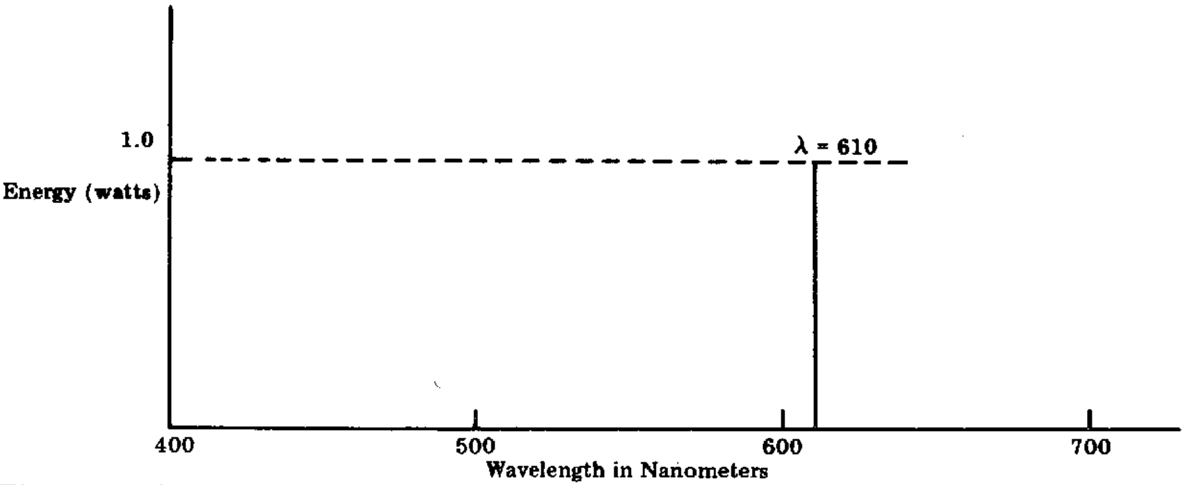


Figure 27. Spectra of a theoretically perfect orange hue with dominant wavelength at 610 nm.

Generally, however, the color results from a *combination* of energies emitted at many wavelengths, each one of which exists in varying proportions. For example, a color orange with a dominant wavelength at 610 nm might have a distribution as shown in Figure 28. The color would then consist of:

Wavelength of Radiation	Units of Energy
600 nm	.1
605 nm	.5
610 nm	1.0
615 nm	.7
620 nm	.3
625 nm	.1

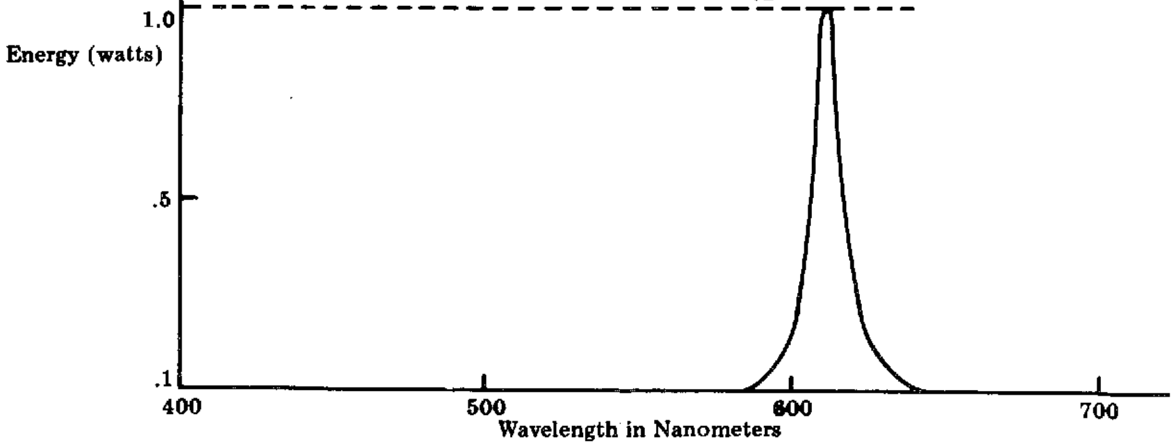


Figure 28. Spectral distribution of an actual orange color with dominant wavelength at 610 nm.

The true significance of spectrophotometric data or spectral distribution data can be illustrated with the aid of Figure 29. Two objects, *a* and *b*, illuminated by the same light source were measured to obtain the spectrophotometric curves. Because of the difference in these distributions, it might be concluded that the two objects possess entirely different visual colors. Correct? No! An observer viewing these objects simultaneously, under the same light source, would correctly state that the colors of *a* and *b* are identical. This example emphasizes one of the most basic principles of spectrophotometry, namely: *that a spectrophotometric curve produces one and only one visual sensation of color to the eye [x, y, Y]; whereas, for any color [x, y, Y] there exists an infinite number of spectral distributions which can generate that color.*

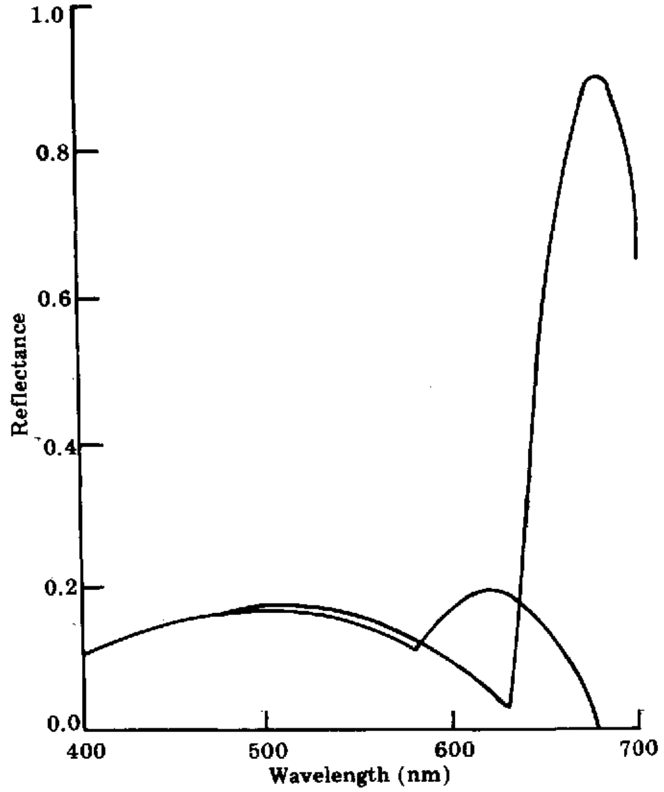


Figure 29. Two spectral distributions can produce the same CIE coordinate (x, y, Y).

It is obvious from this fact that it would be impossible to attempt to generate the spectral distribution of an object knowing only its chromaticity coordinates. Since, however, every curve or signature creates a unique color, it is possible to deduce the visual sensation which that distribution will produce in terms of the coordinates (x, y, Y). Several procedures have been set up to do this:

- Weighted Ordinate Method of Colorimetry
- Selected Ordinate Method of Colorimetry

These two methods will be discussed in the following section.

3.3.1 Reduction of Spectrophotometric Data to Tri-Stimulus Coordinates

The spectral distribution of an object is obtained by the use of a spectrophotometer. This instrument measures the radiation reflected from the object in very narrow spectral regions (say, every 5 nm from 400 nm to 700 nm). The CIE tri-stimulus data is a function of this reflectance, as well as two other variables:

- the spectral distribution of the source illuminating the object
- the spectral response of the human eye

Let R_λ be the inherent reflectance of an object at any wavelength, λ, and H_λ be the amount of light which illuminates the object in the small wavelength interval, $\Delta\lambda$. Figure 30 diagrammatically shows this for $\lambda = 550$. The inherent reflected energy of the object is modified by the source illuminating it. Hence, if $H_\lambda \Delta_\lambda$ is the illuminant at wavelength λ and R_λ is the object's reflectance at λ, then the product of the two, or $R_\lambda \bullet H_\lambda \Delta\lambda$ is the energy which is incident upon the eye. The CIE has specified the visual response of the standard observer (see Figure 24) and these curves are called "weighting functions" of the eye. To determine the tri-stimulus values of the reflected light, it is only necessary to add up the energy associated with these functions x, y, and z for all values of λ. That is,

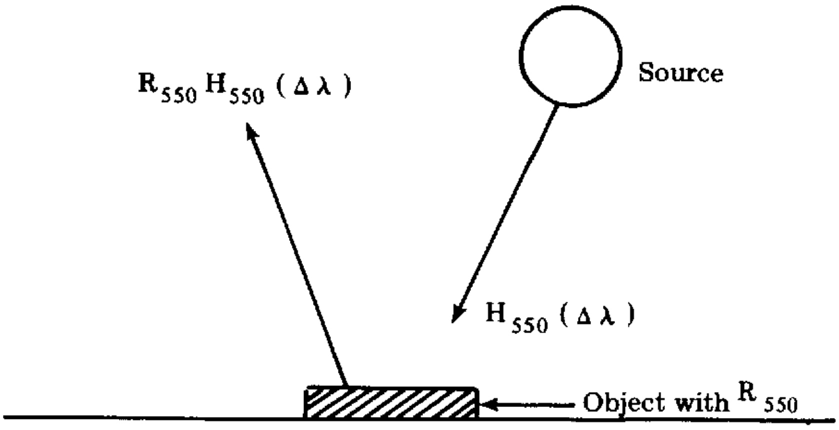


Figure 30. Illuminance and reflected brightness of an object in the spectral region 550 nm + $(\Delta\lambda/z)$.

$$X = \sum \bar{x} \ (R_\lambda H_\lambda \Delta\lambda)$$

$$Y = \sum \bar{y} \ (R_\lambda H_\lambda \Delta\lambda)$$

$$Z = \sum \bar{z} \ (R_\lambda H_\lambda \Delta\lambda)$$

$$X = k\int_{380}^{770} R_\lambda H_\lambda x \ d\lambda$$

$$Y = k\int_{380}^{770} R_\lambda H_\lambda y \ d\lambda$$

$$Z = k\int_{380}^{770} R_\lambda H_\lambda z \ d\lambda$$

3.3.1 Weighted Ordinate Method

This method of computing the tri-stimulus values of an object consists basically of weighting the color matching functions of the eye, x, y, z, by $R_\lambda H_\lambda \Delta_\lambda$. Elaborate tables have been generated containing the product $H_\lambda x$, $H_\lambda y$, $H_\lambda z$ for CIE illuminants A, B, and C. In order to carry out this calculation of tri-stimulus values, the use of Table VI is helpful. The only item to be inserted into this table is the spectrophotometric data. At each wavelength indicated in Column 1, the reflectance of the object should be read from the reflectance curve and placed in Column 2. After multiplication of the reflectance and weighting factors, the results are added separately. That is, the sum of Column 3, the sum of Column 5, and the sum of Column 7 are recorded at the bottom of the sheet and the color coordinates are computed as shown.

Selected Ordinate Method

This second method of reducing spectrophotometric data to tristimulus coordinates is actually quite similar to the weighted method with one major exception. That is, the wavelength intervals Δy are not fixed to be, say 10 nms wide; rather,they are selected so that $H_\lambda x \Delta\lambda$, $H_\lambda Y \Delta_\lambda$, and $H_\lambda z \Delta\lambda$ have the same value throughout the spectrum. Hence, the wavelengths under consideration using the Selected Method are different for different light sources.

Both the Weighted Ordinate and the Selected Ordinate Methods of determining tri-stimulus values from spectrophotometric data are really only approximations. It stands to reason that as the number of ordinates of wavelengths is increased, so is the accuracy of the computation. Unless the Selected Method employs 100 or more wavelength points, it is generally less accurate than the Weighted Methods.

3.3.2 Spectrophotometers and Spectroradiometers

It has been shown that the most fundamental way to analyze the color of an object is to measure its reflected (or transmitted) energy in many small spectral regions. The instruments which perform this task are known as spectroradiometers and they employ either prisms or gratings to isolate these narrow wavelength bands. The sensors which measure the energy may be either photomultiplier tubes or thermopiles.

Spectroradiometers have three basic parts:

- The *input optics* which collect the radiant flux or energy to be measured.
- The *monochromator* which isolates the narrow spectral region to be measured.
- The *detector* which records the energy in appropriate units such as microwatts per centimeter squared per nanometer of the spectrum.

Figure 31 is a schematic of a single prism spectroradiometer.

The energy from the light to be measured enters slit S_1, and by means of lens L_1 is made parallel before being dispersed by the prism. The second slit S_2 may be moved across the spectrum to isolate the wavelength region desired. It stands to reason that as the slits S_1 and S_2 are made smaller the isolated spectral region becomes narrower, but the amplitude of the light falling onto the detector also decreases manufacturers supply sets of slits, S_1, and S_2, to be used for obtaining measurements at different bandwidths.

Table VI

Illuminant "A" — Weighted Ordinate Method

Object Identification:
Analyzed by:

Spectrophotometer:
Date:

Wavelength λ	Reflectance R_λ	$(\bar{x}H)_\lambda$	$R_\lambda \times (\bar{x}H)_\lambda$	$(yH)_\lambda$	$R_\lambda \times (yH)_\lambda$	$(\bar{z}H)_\lambda$	$R_\lambda \times (\bar{z}H)_\lambda$
380		.001		.000		.006	
390		.005		.000		.023	
400		.019		.001		.093	
410		.071		.002		.340	
420		.262		.008		1.256	
430		.649		.027		3.167	
440		.926		.061		4.647	
450		1.031		.117		5.435	
460		1.019		.210		5.851	
470		.776		.362		5.116	
480		.428		.622		3.636	
490		.160		1.039		2.324	
500		.027		1.792		1.509	
510		.057		3.080		.969	
520		.425		4.771		.525	
530		1.214		6.322		.309	
540		2.313		7.600		.162	
550		3.732		8.568		.075	
560		5.510		9.222		.036	
570		7.571		9.457		.021	
580		9.719		9.228		.018	
590		11.579		8.540		.012	
600		12.704		7.547		.010	
610		12.669		6.356		.004	
620		11.373		5.071		.003	
630		8.980		3.704		.000	
640		6.558		2.562		.000	
650		4.336		1.637		.000	
660		2.628		.972		.000	
670		1.448		.530		.000	
680		.804		.292		.000	
690		.404		.146		.000	
700		.209		.075		.000	
710		.110		.040		.000	
720		.057		.019		.000	
730		.028		.010		.000	
740		.014		.006		.000	
750		.006		.002		.000	
760		.004		.002		.000	
770		.002		.000		.000	

Tri-Stimulus Coordinates or	Add Column 4 $\Sigma R_\lambda (\bar{x}H)\ \lambda$ = ( ) X = ( ) X+Y+Z = ( )	Add Column 6 $\Sigma R_\lambda (\bar{y}H)\ \lambda$ = ( ) Y = ( )	Add Column 8 $\Sigma R_\lambda (\bar{z}H)\ \lambda$ = (Z = (
Chromaticity Coordinates	$x = \frac{X}{X+Y+Z}$ = ( )	$y = \frac{Y}{X+Y+Z}$ = ( ) 3-26	$z = \frac{Z}{X+Y+Z}$ (

able VI continued . . . .

Illuminant "B" — Weighted Ordinate Method

bject Identification:
nalyzed by:

Spectrophotometer:
Date:

avelength λ	Reflectance R_λ	$(\bar{x}H)_\lambda$	$R_\lambda x(\bar{x}H)_\lambda$	$(\bar{y}H)_\lambda$	$R_\lambda x(\bar{y}H)_\lambda$	$(\bar{z}H)_\lambda$	$R_\lambda x(\bar{z}H)_\lambda$
380		.003		.000		.014	
390		.013		.000		.060	
400		.056		.002		.268	
410		.217		.006		1.033	
420		.812		.024		3.899	
430		1.983		.081		9.678	
440		2.689		.176		13.489	
450		2.744		.310		14.462	
460		2.454		.506		14.085	
470		1.718		.800		11.319	
480		.870		1.265		7.396	
490		.295		1.918		4.290	
500		.044		2.908		2.449	
510		.081		4.360		1.371	
520		.541		6.072		.669	
530		1.458		7.594		.372	
540		2.689		8.834		.188	
550		4.183		9.603		.084	
560		5.840		9.774		.038	
570		7.472		9.334		.021	
580		8.893		8.396		.016	
590		9.728		7.176		.010	
600		9.948		5.909		.007	
610		9.436		4.734		.003	
620		8.140		3.630		.002	
630		6.200		2.558		.000	
640		4.374		1.709		.000	
650		2.815		1.062		.000	
660		1.655		.612		.000	
670		.876		.321		.000	
680		.465		.169		.000	
690		.220		.080		.000	
700		.108		.039		.000	
710		.053		.019		.000	
720		.026		.009		.000	
730		.012		.004		.000	
740		.006		.002		.000	
750		.002		.001		.000	
760		.002		.001		.000	
770		.001		.000		.000	

i-Stimulus
oordinates
or

Add Column 4
$\Sigma R_\lambda(\bar{x}H)_\lambda$ = ( )
X = ( )
X + Y + Z = ( )

Add Column 6
$\Sigma R_\lambda(\bar{y}H)_\lambda$ = ( )
= ( )

Add Column 8
$\Sigma R_\lambda(\bar{z}H)_\lambda$ = ( )
= ( )

romaticity
oordinates

$x = \frac{X}{X+Y+Z}$ ( ) $y = \frac{Y}{X+Y+Z}$ ( ) $z = \frac{Z}{X+Y+Z}$ ( )

-3-27-

Table VI continued . . .

Illuminant "C" — Weighted Ordinate Method

Object Identification: Spectrophotometer:
Analyzed by: Date:

Wavelength λ	Reflectance R_λ	$(\bar{x}H)_\lambda$	$R_\lambda \times (\bar{x}H)_\lambda$	$(\bar{y}H)_\lambda$	$R_\lambda \times (\bar{y}H)_\lambda$	$(\bar{z}H)_\lambda$	$R_\lambda \times (\bar{z}H)_\lambda$
380		.004		.000		.020	
390		.019		.000		.089	
400		.085		.002		.404	
410		.329		.009		1.507	
420		1.238		.037		5.949	
430		2.997		.122		14.628	
440		3.975		.262		19.938	
450		3.915		.443		20.638	
460		3.362		.694		19.299	
470		2.272		1.058		14.972	
480		1.112		1.618		9.461	
490		.363		2.358		5.274	
500		.052		3.401		2.864	
510		.089		4.833		1.520	
520		.576		6.462		.712	
530		1.523		7.934		.388	
540		2.785		9.149		.195	
550		4.282		9.832		.086	
560		5.880		9.841		.039	
570		7.322		9.147		.020	
580		8.417		7.992		.016	
590		8.984		6.627		.010	
600		8.949		5.316		.007	
610		8.325		4.176		.002	
620		7.070		3.153		.002	
630		5.309		2.190		.000	
640		3.693		1.443		.000	
650		2.349		.886		.000	
660		1.361		.504		.000	
670		.708		.259		.000	
680		.369		.134		.000	
690		.171		.062		.000	
700		.082		.029		.000	
710		.039		.014		.000	
720		.019		.006		.000	
730		.008		.003		.000	
740		.004		.002		.000	
750		.002		.001		.000	
760		.001		.001		.000	
770		.001		.000		.000	

Tri-Stimulus Coordinates or

Add Column 4
$\Sigma R_\lambda (\bar{x}H)_\lambda$ = ( )
X = ( )
X + Y + Z = ( )

Add Column 6
$\Sigma R_\lambda (\bar{y}H)_\lambda$ = ( )
Y = ( )

Add Column 8
$\Sigma R_\lambda (\bar{z}H)_\lambda$ = ( )
Z = ( )

Chromaticity Coordinates

3-28

$x = \frac{X}{X+Y+Z}$ = ( ) $y = \frac{Y}{X+Y+Z}$ = ( ) $z = \frac{Z}{X+Y+Z}$ = ( )

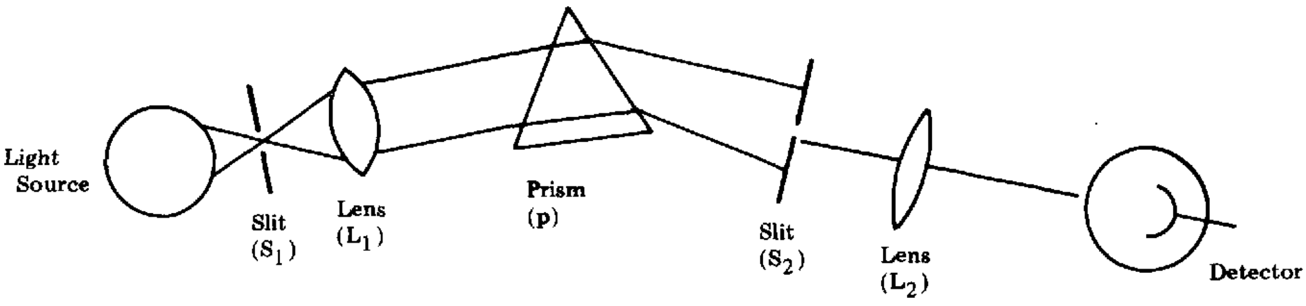


Figure 31. Schematic of a single prism spectroradiometer system.

The primary advantage to the use of spectroradiometers is that the resultant data is not relative; it is an absolute quantity. The data can be made relative by measuring simultaneously both the absolute energy illuminating the object (H_λ) and the absolute energy being reflected or transmitted (R_λ). The ratio of R_λ/H_λ is then the relative reflectance or transmission of the object.

Several precautions must be taken, however, if meaningful spectroradiometric data is to be obtained:

1. A standard lamp must be purchased from the National Bureau of Standards which is calibrated with respect to the energy it emits in each spectral region. Generally, these values are supplied at every 10 nanometers. Figure 32 is an example of such a calibration. Notice that this lamp must be operated at an *exact* voltage and amperage, at an *exact* distance from the spectroradiometer.
2. The spectroradiometer is then placed at the prescribed distance; the output of the lamp is measured at the wavelengths shown on the calibration table by the spectroradiometer.
3. Prior to using any spectroradiometer data, it is essential that the dark current of the photomultiplier (detector) be measured and subtracted from the readings. The exact procedure for this consists of closing off all light from the monochromator and detector. The output from the spectroradiometer is measured at each wavelength given in the calibration table and these values are subtracted from the data.
4. A correction curve is generated by plotting the actual spectroradiometer lamp readings along the x axis and the calibrated lamp readings along the y axis.
5. Subsequent spectroradiometric data must 1) have the photo tube dark current subtracted and 2) be corrected to the standard lamp prior to use.

The following data sheet (Figure 33) greatly facilitates the taking of accurate spectroradiometric measurements.

In spite of the tedious task of calibration, spectroradiometers are the only instruments capable of obtaining the accurate in situ spectral measurements of objects which are essential for determining subtle color differences in the environment. Spectroradiometers are most often employed for field measurements when a physical disturbance of the object will significantly alter its spectral reflectance. For example, plants lose water and nutrients within minutes after being removed from the

Energy Distribution of Illuminant A

Wavelength	E_A	Wavelength	E_A
380	9.79	590	121.73
390	12.09	600	129.04
400	14.71	610	136.34
410	17.68	620	143.62
420	21.00	630	150.83
430	24.67	640	157.98
440	28.70	650	165.03
450	33.09	660	171.96
460	37.82	670	178.77
470	42.87	680	185.43
480	48.25	690	191.93
490	53.91	700	198.26
500	59.86	710	204.41
510	66.06	720	210.36
520	72.50	730	216.12
530	79.13	740	221.66
540	85.95	750	227.00
550	92.91	760	232.11
560	100.00	770	237.01
570	107.18	780	241.67
580	114.44		

Figure 32. National Bureau of Standards calibration sheet for standard illuminate "A" source.

SPECTRORADIOMETER DATA

BY: ______________________

TARGET NUMBER______ SCAN ______ DATE ______________________ STARTING TIME ______________

WAVELENGTH & TIME	INCIDENCE UNIT	REFLECTANCE UNIT
START VIS CALIB.		
START VIS D.C.		
START VIS. TIME		
380		
400		
425		
450		
475		
500		
525		
550		
575		
600		
625		
650		
675		
700		
725		
750		
END VIS DC		
END VIS CALIB.		
END VIS TIME		
START IR CALIB.		
START IR DC		
START IR TIME		
750		
800		
850		
900		
950		
1000		
1050		
1100		
1150		
1200		
1250		
END IR DC		
END IR CALIB.		
END IR TIME		

soil and their leaf reflectances change drastically; also, when soils are dug up and moved into a laboratory for spectral reflectance analysis, changes take place in their spectra owing to a disturbance of the surface and subsurface layers, moisture content, etc. There are, however, some cases in which objects may be moved from their environment and still maintain their reflectance properties. For example, single rocks, certain types of marine fauna, man-made objects such as asphalt, roofing materials, etc.

Adequate spectral measurement of such objects can be made in the laboratory using a spectrophotometer, which produces the reflectance (or transmission) of an object in narrow spectral regions *directly*. This is accomplished by measuring simultaneously both the amount of light falling on the object (H_λ) and the light which is reflected from it (R_λ). The ratio of $(R_\lambda)/(H_\lambda)$ x100 is the percent reflectance. The light incident upon the object is generally a standard Illuminant "A" which is incorporated into the spectrophotometer, while the sensing mechanism may be either a photodetector or the human eye. Photoelectric spectrophotometers may be recording or non-recording instruments. The former requires that the data be taken wavelength by wavelength from a meter, whereas the recording instrument *automatically plots* the variations in transmission or reflectance as a function of wavelength.

Photoelectric spectrophotometers have almost completely replaced the visual instruments because of their greater speed and convenience. A schematic of a single pass photoelectric spectrophotometer is shown in Figure 34.

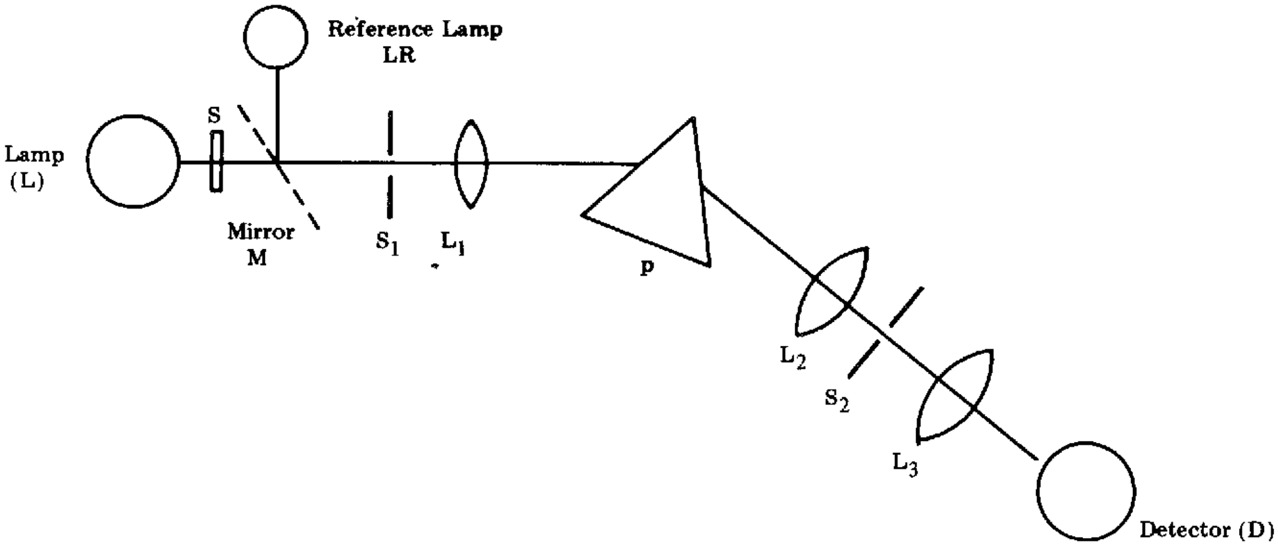


Figure 34. Schematic of a photoelectric spectrophotometer.

Two light sources (Illuminant A) are employed in this instrument: lamp L provides the illumination for the sample S, while L_R is the reference source. A first surface mirror M may be inserted into the path to permit measurement of the standard lamp L_R. When it is removed from the light path, illumination from the sample S is measured. The light, after passing through the entrance slit S_1 is dispersed by the prism P and an enlarged image of S_2 is formed on the detector D. At any given wavelength and with the mirror M removed, the output of D is measured(this value is proportional to the radiant flux transmitted through the sample). M is then placed in the path and the reference source is measured at the same wavelength. The ratio of the transmitted (or reflected) flux at any wavelength to the amount of flux in the reference beam at that wavelength is known as the percent transmittance or reflectance.

Not all spectrophotometers operate on this single beam principle, i.e., the photodetector sensing first the reference source and then the sample. Many units now incorporate a double beam principle in which the flux from the reference source and the sample are simultaneously measured; their outputs are then electronically amplified and divided to provide the spectrophotometric curve directly.

It should be noted that most spectrophotometers have been designed to measure the percent transmission of a sample, but attachments are available to convert the unit into one which will measure percent reflectance. One such attachment consists of an intergrating sphere coated inside with magnesium oxide (MgO). Referring to Figure 35, light from the source L is directed into the integrating sphere onto the sample. The sample reflects the radiation in all directions and after many reflections off the walls of the sphere, some of the light will pass through the aperture A and be directed to the dispersion prism or grating and thence to the photodetector. The integrating sphere also contains two caps, either one of which may be placed over the aperture at C. These are necessary in order to measure either of two types of reflectances: diffuse and specular. The specular component of reflected light is that portion which is commonly called glossy or shiny. The diffuse component consists of the flat or matte portion of the reflected light. The diffuse and specular components of reflected light for some common materials is given in the following table:

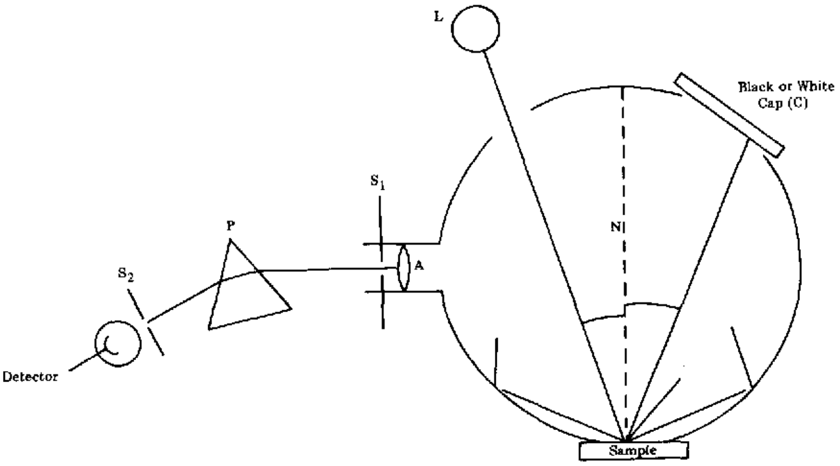


Figure 35. Reflectance attachment for spectrophotometer:

Table VII

Material	% Specular Reflection	% Diffuse Reflection
Cardboard	30	70
Silver Foil	99	1
Newspaper	11	89
Asphalt	40	60
Blotter Paper	.2	99.3

If, for example, one wishes to measure the total reflectance of a sample without regard for its specular or diffuse components, then the white cap is used over the aperture at C. If, however, one wishes to eliminate the specular component from the resultant reflectance measurements than the black cap (generally made of velvet or some other light absorbing medium) is placed over the aperture at C. One will notice in Figure 35 that the angle (θ) between the normal to the sphere N and the source L is the same as that between N and C. Hence, the entire specular component reflected from the sample will fall onto the black cap at C and be totally absorbed by it.

The choice of whether to purchase a spectrophotometer or a spectroradiometer is a rather simple one. It is almost totally dependent upon whether the objects to be measured must be analyzed in situ or if they belong to that sub-class of objects whose reflectance will *not* change if disturbed from their environment. The effort required to maintain the spectroradiometer in calibration may also be a factor. Unless a sufficient number of measurements warrant its purchase, it is often easier and cheaper to either rent or lease the spectroradiometer or to sub-contract that phase of effort to an organization which already owns an instrument and is familiar with it. Chances are that such organizations already have the calibration and data reduction simplified so that considerable time and effort can be saved.

The purchase of a spectrophotometer is obviously dependent on the kind of specimens which are to be analyzed: transmitting, reflecting, or fluorescing samples. However, a major consideration is also the sample size; each spectrophotometer is extremely limited by the maximum dimensions which the specimen holders can accommodate. Generally, this ranges up to a few inches in diameter. Also, consideration should be given to the average sample stability to light and heat. Depending upon the design of the instrument, the illumination incident upon the sample may be either confined to a small spectral region or contain all wavelengths of the spectrum from the near ultraviolet through the infrared. An instrument designed to illuminate with the entire spectrum causes a good deal of heat (infrared) energy to be focused on the specimen. Some samples change their spectral characteristics with the application of heat or, due to their instability, have a tendency to fade. An example of such a material is the well-known Eastman Kodak gelatin filters. These filters are quite unstable to light and heat even when sandwiched between glass.

The choice of a recording or non-recording spectrophotometer is dependent upon the number of samples to be analyzed per day or per week and the speed with which the resultant data is required. A measure of the visible spectral reflectance or transmittance and a plot of this data may only take two minutes on a recording instrument. The same task on a non-recording spectrophotometer can take up to about 60 minutes to accomplish. When large volumes of spectral curves must be generated, the recording instrument can supply the data in several days, against perhaps months for the non-recording. There is, however, the additional consideration of cost; unless one is anticipating the analysis of hundreds of specimens per year, it may not be worth the initial high price of the recording spectrophotometer.

The spectral range of the instrument is also of importance; most can be purchased with sensors (photomultipliers) which cover either the near-ultraviolet spectrum (200-380 nm), the visible (380 -750 nm), or the near infrared spectrum (750-1800 nm). Often, two photomultipliers (say, visible and infrared) are installed in the spectrophotometer with the operator being able to select which spectral region he desires to scan. The near-ultraviolet sensor is generally employed to measure the characteristics of fluorescent materials and the near-infrared is usually employed in the study of vegetation reflectance and heat absorbance in objects.

The choice of a spectrophotometer is lastly dependent upon whether customized components are necessary. For example, certain units may be modified to punch out the transmission or reflectance data onto cards for future analysis in a high-speed computer. Consultation with the manufacturers of color measuring instruments, prior to purchase, will prove extremely valuable in terms of money saved and knowledge gained. The characteristics of several spectroradiometric and spectrophotometric systems are now presented.

The incidence spectroradiometer manufactured by Instrument Specialties Company uses a wedge interference filter system enabling the spectrum from 380 to 1250 nanometers to be continually scanned. The spectroradiometer is equipped with a diffusing screen so that its directional response is proportional to Lambert's cosine law. This method of measuring sunlight is pertinent since incident global radiation falls upon the earth's surface and is reflected into an entire hemisphere regardless of its original direction of propagation. True cosine response also eliminates the need for precise aiming of the instrument. This incidence spectroradiometer (ISCO) measures in units of energy rate intensity per bandwidth such as microwatts per centimeter square per nanometer. This latter system of units is most meaningful for measurements of illumination; a graph of spectral distribution of radiant intensity versus wavelength can be obtained and the area under such a curve will be numerically and dimensionally equal to energy available in the wavelength interval of interest. The ISCO spectroradiometer is capable of measuring from .01 to 1000 microwatts per centimeter square per nanometer. These values correspond roughly to illumination levels of .03 to 30,000 foot candles.

The accurate use of the ISCO spectroradiometer requires verification, periodically, during the experiment. A spectral standard lamp, serially numbered and individually calibrated against the National Bureau of Standards is used. The lamp is of the ribbon filament tungsten type and has a nominal accuracy of plus or minus five percent relative to the NBS standard. The precise regulation of the current to the lamp is maintained by a precision electrical power supply unit.

The half bandwidth of this spectroradiometer which may be used to measure the incident illumination is approximately 15 nanometers in the 380 to 750 range and 30 nanometers in the 750 to 1250 range. Stray light response to unwanted wavelengths of 15 nanometers bandwidth and far from the wavelength of interest is usually in the order of .01 percent. Stray light error results in a too high reading and limits the accuracy of measurement of low intensity spectral energy in the presence of high-intensity radiation in different wavelengths. The most severe stray light error results when measuring the short wavelengths (in the 400 nanometer region) of red rich light sources, such as solar radiation in the afternoon. This ISCO instrument reads approximately 3 percent too high at 400 nanometers when measuring a standard 2800 degree Kelvin source because of stray light passage of longer wavelengths. This amount of error may be compensated for by placing a blue absorbing filter over the sensing head and noting the amount of stray light indicated on the meter. The value is then subtracted from the measured intensity to determine the correct values throughout the wavelength region.

Periodic calibration of the incidence spectroradiometer allows an accuracy of plus or minus seven percent in the long wavelength of the spectrum, and plus or minus ten percent in the short wavelength of the spectrum. Most of this error, of course, comes from uncertainty in the secondary standard used. The relative accuracy of all points with respect to each other throughout the wavelength measured is approximately plus or minus three percent.

The E.G. & G. Model 585 spectroradiometer system allows the user to make measurements with direct meter and recorder readout of the integrated energy from pulsed light sources and the average power of continuous light sources.

To measure the amount of reflected radiation from the target, two separate detectors are used; one for the visible range from 350 nm to 750 nm, and the second for the near infrared range from 750 nm to 1250 nm. Both are attached to the readout unit which displays the output on an analog meter. Power for the readout unit is supplied by internal battery so the entire system is completely portable.

The reflectance spectroradiometer system allows absolute measurements of the solar radiation reflected by objects of interest. By means of a grating monochromator, these energy and power readings can be made at selected wavelengths over a bandwidth determined by the grating and the slits. This instrument basically consists of an optical system which limits the entrance of energy to a twelve degree field, a monochromator grating to spectrally isolate the visible energy to a five nanometer halfband pass or a monochromator grating to spectrally isolate the infrared energy to a ten nanometer halfband pass, and a detector head to sense the magnitude of the incident energy.

The Gamma Scientific Model 3000/3300 scanning spectroradiometers are instruments designed for the automatic, rapid, absolute spectral analysis of radiant energy sources. The Model 3000 system is designed to cover the visible spectrum from 400 nm to 700 nm, while the 3300 system covers the near infrared region from 600 nm to 1000 nm. The optical heads are interchangeable so that the spectrum can be scanned from 400 to 1000 nm with the two heads, a single control unit and x, y recorder. A digital package is also available providing digital output for both wavelength and power from the spectroradiometers. This attachment allows direct interfacing with digital logging and computer systems. The near infrared S1 photomultiplier is thermoelectrically cooled and a compensation system flattens the sensitivity of this unit from 600-1000 nm.

In view of the present interest in spectral radiometric study and characteristics of agricultural cover, Exotech has developed a versatile field instrument (Model 20) capable of taking reliable radiometric data under rigorous field conditions. The Model 20 is based on a circular variable filter approach which is the best way to obtain a simple, rugged, field instrument with high radiometric efficiency.

The complete instrument is comprised of two separate optical units with a single control unit containing signal processing electronics and power supplies. The short wavelength optical unit covers the spectral range 0.35μ to 2.5μ and is capable of measuring spectral reflectivity by making use of an integral reference surface that provides data on incident radiation. The long wavelength optical unit covers the spectral range 2.8μ to 14μ and contains a temperature controlled black body reference.

The field of view of the instrument is 1° with primary lens inserted and 15° with primary lens removed.

System signal to noise ratio is greater than 1,000:1 over the wavelength region 0.35 to 2.3 microns, greater than 10,000:1 over the wavelength region 0.5 to 1.5 microns (for a target with 100 percent reflectivity), and greater than 100:1 over the wavelength region 3.5 to 14 microns.

The instrument operates on 115 volts AC+20 percent, 60 cps + 1 cps and requires less than 150 watts. The system incorporates an internal blackbody to which all radiance measurements are referenced, as well as an incident radiation reference. The instrument provides capability for automatic alternate scans of incoming or target radiance.

The collecting optics are able to focus from infinity to one (1) meter or less, and a photographic adapter is provided to permit a Hasselblad 70mm camera to photograph the target scene through the sighting telescope. The system provides signals suitable for a real time display of the radiation received by the instrument as a function of wavelength. These signals are suitable for driving an oscilloscope, a strip chart recorder or an x-y plotting type recorder, and a tape recorder.

The unit is capable of operation within specifications over the temperature range -20°C to +55°C and over the humidity range 0 to 100 percent providing that condensation does not occur internal to the instrument.

Color-Rad is an instrument that utilizes an array of sixteen narrow bandpass interference filters. As such, it provides a quantitative spectral analysis of luminous sources having candlepower ratings as small as 0.5 candlepower. It is the only known practical instrument at the present time that can provide this type of abridged spectral analysis of colored luminous sources of such low candlepower and provide data for accurate (x, y) chromaticity control. In addition, Color-Rad uses separate built-in tristimulus X, Y and Z equal energy filters for simplified color difference measurements. Their use reduces to a minimum the arithmetical computation required to obtain approximate (x, y) locations in color space when working in production matching of luminous sources or source-filter combinations. Therefore, it is possible with the Color-Rad to obtain an abridged spectral energy survey and/or a tristimulus approximation of a given luminous source. A reference source is used in all measurements. The standards supplied are tungsten lamps calibrated and controlled to serve as reference sources of known spectral emittance. Other standards, such as known-source and known-filter combinations, may be used as applicable.

An adaptation of the widely used CARY 14 spectrophometer, the CARY spectroradiometer has been developed for special radiation measurements and comprehensive studies in fields such as space physics, chemistry, and biology. It is the first capable, direct reading instrument combining wide spectral range, high sensitivity, and resolving power with values of accuracy, speed, and convenience.

An integrating sphere system eliminates problems caused by differences in source geometry or detector response, while the rapid alternation removes uncertainties occurring from electronic drift. The system is sensitive only to changes in the known/unknown source intensity ratio. The CARY spectroradiometer is capable of measuring ratios of two beam intensities with an accuracy of 2 percent for reasonably intense sources. The spectral bandwidth is less than 0.1 nm from 360 nm to 600 nm. A wavelength cam system enables the spectroradiometer to be pre-programmed from the known irradiance versus wavelength characteristics of the standard lamp. In this way, the ratio measurement between the known and unknown lamps is recorded as the absolute irradiance of the unknown lamp on a linear scale.

The Bausch & Lomb Spectronic 20 spectrophotometer is available in two models with a wide selection of accessories which make colorimetric or spectrophotometric measurements accurate, time-saving, and inexpensive. The unit is a single beam, ratio indicating, spectrophotometer, usable in either a transmittance or absorption mode. It may be used as a spectrophotometer or as a colorimeter. As a spectrophotometer, the certified diffraction grating accurately pinpoints absorption measurements of quickly selected wavelengths from 340 nm to 600 nm without changing phototubes or using filters. As a colorimeter, readings in optical density or percent transmittance are taken directly from the scale. The spectral range can be changed from 340 nm to 600 nm with a change of supplementary phototube and infrared transmitting filter. No adjustment of slit width or sensitivity control is necessary since dispersion of a grating is linear and output constant. The fixed slit produces a constant, narrow bandpass of 20 nm over the instrument range.

The Perkin Elmer SG-4 spectrophotometer permits detailed spectral analysis of remote source radiation from the ultraviolet to the far infrared.

It is particularly useful for meteorological/atmospheric and geological studies, measurement of emissivity and reflectance of coatings and surfaces, spectral analysis of combustion processes and products, light sources and plasmas.

The instrument employs a four-inch reflecting telescope, an oscillating-grating monochromator, slit transfer optics, and a detector/amplifier selected for the wavelength interval of interest. Gratings, filters, spectral slits, and field stops are easily interchanged, as are the detector/amplifier modules which are prefocused and self-aligning. When appropriate, these modules include cryogenic fittings for liquid-nitrogen transfer. Use of the SG-4 is facilitated by selectable automatic gain control, self-calibration, a reflex eyepiece, and the provision for remote operation, including filter selection.

Baird-Atomic's Model SF-100 fluorescence spectrophotometer is a compact instrument specifically designed to meet the requirements of those engaged in the field of fluorescence.

The monochromators may be scanned automatically or manually, covering both the excitation and fluorescent spectra from 220 to 700 nanometers. Readout is direct, using the front panel meter. Output jacks are provided for driving such auxiliary readouts as oscilloscopes, x-y recorders, or linear recorders. Radiation from a xenon light source is dispersed by a monochromator which permits selection of the wavelength incident upon the sample. A second monochromator scans the fluorescent light emitted by the sample. Light of the selected wavelength is transmitted to the photomultiplier tube detector which converts the light energy into an electrical signal which is proportional to the light intensity. This signal is amplified and indicated on the front panel meter.

Selection of the excitation wavelength and the fluorescent wavelength are independently controlled by cams which adjust the angles of the gratings. A series of three position slits are located at the entrance slit of the excitation monochromator, at both the entrance and exit slits of the sample chamber, and at the exit slit of the second monochromator. Independent choice of each of these allows the operator to choose the optimum combination of sensitivity and resolution.

The use of larger slits allows more light to pass through the monochromator to excite the sample which, in turn, causes the sample to emit more fluorescent radiation. This is very advantageous when working with samples at low concentrations because a maximum amount of energy is made available without any sacrifice in resolution.

3.4 Color Density

In addition to the Muncell, the colorimetric and spectroradiometric methods of measuring color, some mention should be made regarding the use of densities as a color specification. This technique is primarily used in conjunction with color transparencies, and computer programs have been established to convert the date to the commonly used CIE system (see Section 3.2.4).

The measurement of the color density of a reversal or negative film is complicated by the nature of the dye images formed. Each dye has significant absorption throughout the spectrum so that the color density measurement of one layer is affected by the dyes in the other two layers. Color density measurements are usually made for either of two reasons: (a) to determine the effect which the color film has upon a light beam transmitted through it, or (b) to determine the composition of the image in terms of the individual dyes which form it. Because of this situation, several methods of measuring color densities have been devised and each method will produce different information about the image. Figure 36 shows a block diagram of various types of color density measurements.

Analytical densities consist of measuring the individual absorptions of the dye layers of color films. Such measurements can indicate the exact composition of the image in terms of the amounts of dyes present. To study each dye separately, the tri-pack color material must be exposed so that only a single layer of dye is formed. As such, they are extremely difficult to obtain and are often specified as only valid for a particular detector. Analytical density analysis is usually employed when extreme accuracy is required, such as the evaluation of color film manufacturing tolerances.

Integral color density measurements, however, are used to evaluate the *total* effect of the three dye layers and are employed in the processing of color films. There are several types of integral color density measurements. Spectral integral densities are an indication of the wavelength by wavelength absorption characteristics of the film image. That is, if the transmission of the tri-pack, at any wavelength, is defined as T_λ, then the integral density of the film is $D_\lambda = - \log T$. A spectrophotometer is generally employed as the measuring device and the final data consists of the spectral transmission characteristics of the entire image in terms of density.

Integral *printing* density measurements are used to define the exposure required for each dye layer in order to reproduce an acceptable positive. The exposing intensity is altered as a function of the print material sensitivity. For example, printing densities may be measured in a color densitometer with filter-photocell sensitivites which approximate that of the print material.

Colorimetric densities differ from the printing densities in that the filter-photocell sensitivities must be a set of visual, three-color mixture curves (for example, Figure 26). The primary advantage of the use of this method of color density measurement is that the results bear a close correspondence to the visual appearance of the image.

Three filter color densitometers employ an *arbitrary* set of three filters: red, green, and blue. Since no specification of the total system sensitivity is given, the measurements are only used to match the image to a standard. They are relatively easy to obtain and are, therefore, used for processing control of color films.

3.5 Summary

- The Muncell System of color specifications is based upon the visual appearance of the object in terms of hue, value, and chroma.
- The CIE colorimetric system specifies the color of objects in terms of mathematical tristimulus or trichromatic coefficients.
- Any color can generally be matched by the mixture of at least three independent primary colors.
- Adding an equal amount of light from each primary to the color will have the effect of desaturating it.
- Hue may be altered only by changing the proportions of primary in the color mixture.
- None of the additive color primaries may be matched by a mixture of the other two.
- Color specifications may be transformed from one set of primaries to another by determining the transformation coefficients.
- Colorimeters will directly measure the tristimulus values and trichromatic coefficients.
- The spectrophotometric system of color specification describes the distribution of the color as a function of wavelength. The data may be readily converted to colorimetric units using the selected or weighted ordinate method.
- A given spectroradiometric curve will produce one and only one color; but, any color may be be produced by any number of spectroradiometric curves.

Color Density

Integral Density — measurement of total effect of the three dye layers together.

3 Filter Density — used for process control to determine if sample matches standard. Red, green, and blue filters are used.	Colorimetric Density — predicts what color will be when viewed by an observer.	Spectral Density — density measured on spectrophotometer to tell wavelength by wavelength the absorption of the color image.	Printing Density — indicates effect of a color film when printed on a particular material with a particular printer.

Analytical Density — measurement of the effect of each of the dye layers separately.

Analytical Spectral Density — measurement of the effect of each of the dye layers separately.	Equivalent Neutral Density density of the neutral gray which would visually be formed if appropriate amounts of the other two dyes were added to it.	Equivalent Neutral Printing Density — same as equivalent neutral density except that a printing material is used instead of the eye as receptor.

Figure 36. Block diagram of various types of color density measurements.

- The color of an object is dependent upon the spectroradiometric distribution, the illuminate and the standard observer's eye sensitivity.
- Spectroradiometers are used for in vivo spectral reflectance measurements in *absolute* units.
- Spectrophotometers produce relative reflectance data and are generally unsuitable for field measurements.

CHAPTER 4

METHODS OF RELATING GROUND PHENOMENA TO FILM DENSITY AND COLOR MEASUREMENT

The primary objective of aerial photography is to ultimately obtain quantitative information about the environment. It has been shown that such information is very often related to the inherent spectral distributions or colors in the scene. The final density and color of either an additive or subtractive aerial image, however, is a function of many variables besides the spectral reflectance characteristics of objects, namely:

1. The spectral distribution of illuminant.
2. The atmospheric haze between the ground and the aircraft.
3. Effect of secondary reflections from ground objects.
4. Camera exposure.
5. Processing conditions.
6. Viewing illumination.

Since not all of the above variables can be controlled during the exposure stage, we must at least make provisions for their measurement so that compensation can be made at the viewing stage. To facilitate colorimetrically accurate and repeatable photographic data and to relate these results to the environmental conditions present, the following should be provided for:

- the location of "standard" objects in the scene,
- the collection of *complete* ground truth for correlation with the imagery,
- a valid method of correcting the image chromaticity data so that it is a true representation of ground objects.

4.1 Ground Reference Targets

Ground reference targets usually consist of six neutral gray scales ranging from black to white with nominal reflectances of 4%, 8%, 16%, 32%, 64%, and 88%, as well as four color panels — red, green, blue, and yellow. The first consideration in the fabrication of such targets is, of course, the physical size required. It is essential that when photographed onto the film, their images be large enough for measurement on a densitometer and colorimeter. Targets are made in sizes about 20' x 20' which, if larger ones are required, may by placed in an array. For example, four targets (20' x 20') placed in a square yield a target 40' x 40'. The size of 20' x 20' is rather arbitrary, but since the canvas substrates weigh about 50 pounds each, a panel of this size can easily be handled by one man.

In addition to these physical considerations, the targets should be non-specular and although they will not be perfectly diffuse, the highlights or bright spots reflected from them should be minimal. This condition is placed on the targets so that regardless of sun or camera angle to the targets, their reflectance will be almost uniform. In addition to being diffuse, the neutral gray targets must exhibit the same reflectance values throughout the spectrum. Figure 37 shows the reflectance of several gray targets from 380 nm to 750 nm. These flat distributions are about as good as manufacturers are capable of producing. Ground reference targets are subjected to considerable amounts of solar illumination and hence they should either be treated or the coating should be selected in order to minimize fading. Targets fulfilling all of these conditions are manufactured by Data Corporation, Ohio, although their cost is quite high. If, however, a considerable amount of imagery is obtained throughout the year, such targets are a worthwhile purchase and hold up very well to the abuses which are a natural consequence of field work. It should be mentioned that Data Corporation will also rent the targets for photographic tests and will provide the personnel to handle them.

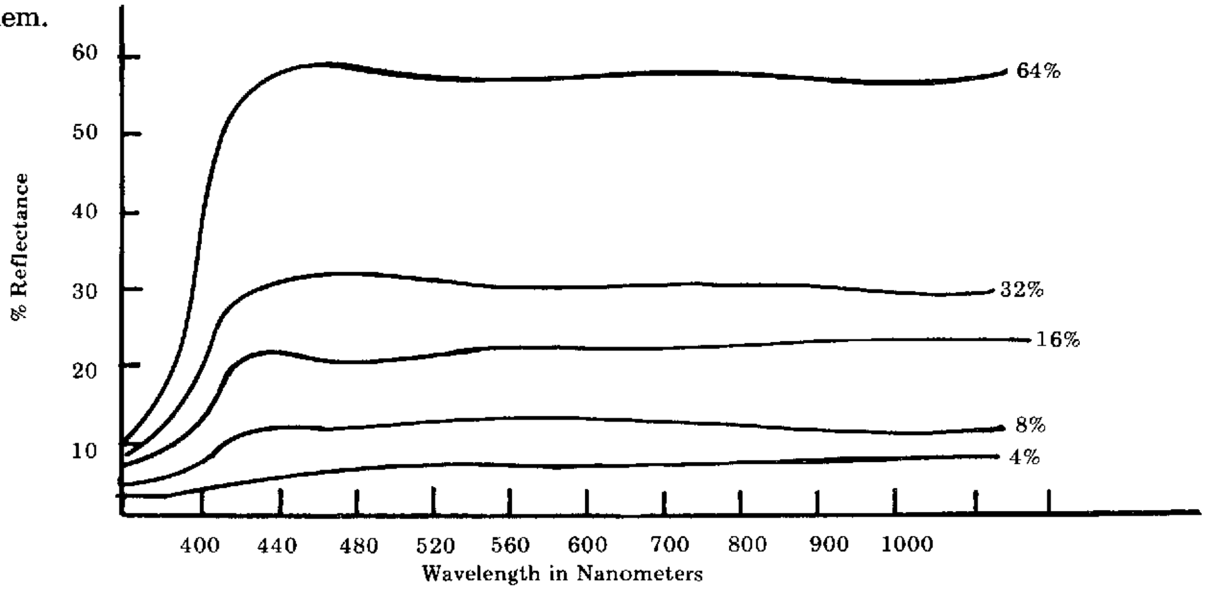


Figure 37. Spectral reflectance curves for Data Corporation gray scale targets with nominal reflectances of 4%, 8%, 16%, 32%, and 64%.

In addition to the ground targets discussed above, another set may be needed for special studies, such as underwater investigations. In this particular case the substrate, as well as the coatings, must be resistant to the hydro-environment including biological growth, natural breakdown, and tidal currents. They must also be retrievable; mounting them in a suitable frame with shock cord will maintain them in a linear array which can be lowered to any desired depth. A typical arrangement for mounting sub-surface targets is shown in Figure 38. Because of their high costs, targets should be manufactured so that they may be used in as many environmental situations as possible.

4.1.1 Colorimetric and Spectrophotometric Calibration of Targets

The use of ground targets to relate final densities or colors in the photographic imagery to objects in the scene requires that the panels be calibrated prior to use.

The initial spectral calibrations of the targets should be performed in the laboratory using an NBS standard source and regulated power supply. Target coatings often change with time and, although the manufacturers generally supply a graph of the nominal reflectances, it is worthwhile to check these values periodically. A special target calibration notebook should be kept in which the repeated chromaticity and spectrophotometric data on the reference panels is logged. This gives a clear indication of the effects of their exposure to solar energy, dirt, etc., and a constant comparison can be made with swatches of panel material generally supplied with the targets. These swatches are about 1' x 1' square and, since they were manufactured at the same time, have exactly the same substrate and coatings as the reference panels.

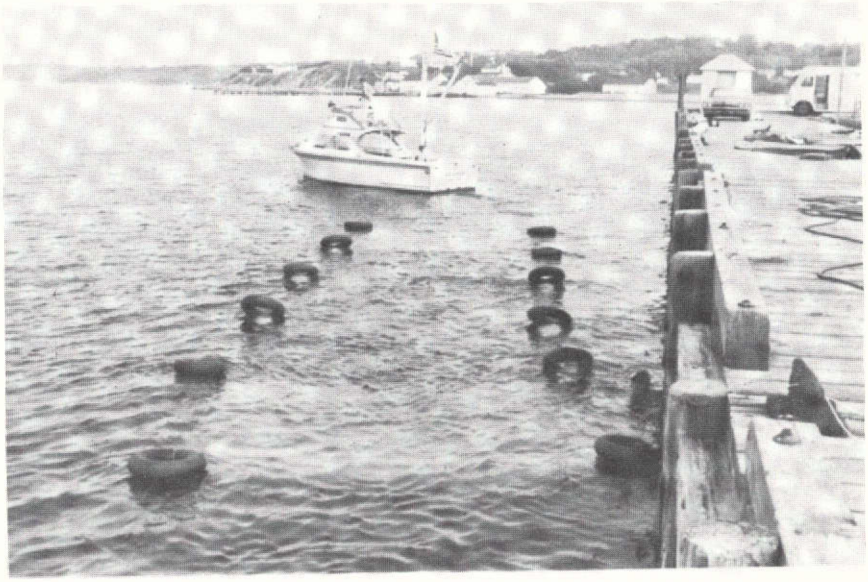


Figure 38. Sub-surface targets mounted in a frame can be submerged to any desired depth with ease.

Using a tri-stimulus colorimeter, laboratory measurements of the chromaticity coordinates of each color and gray panel are measured. Most colorimeters operate fairly rapidly so that it is possible to obtain large sets of data in short periods of time. For this reason, at least five sets of chromaticity coordinates should be measured on each of the reference panels. An average of these five sets will then yield a more valid set of chromatic coefficients (x, y, Y). Usually, these laboratory measurements are taken using a standard A source as the illuminant. The colorimeter measures the reflectance of the target against a white magnesium oxide standard, *both* substances being illuminated by the same source. The resulting data represents the *inherent* color of the panel. However, when measuring the chromaticity coordinates of the reference targets in the field, the illuminating source for the panels is the sun and skylight, although the illuminant for the white magnesium oxide standard must still be illuminant A. As far as the colorimeter is concerned, it is still measuring the chromaticity of the panels using illuminant A for both the standard and the targets. It would record a different inherent color for the panels, however. This difference between the laboratory and field CIE coordinates only represents the color discrepancy between the solar illuminant and illuminant A. Since the *inherent* color of the panels in terms of the CIE coordinates were generated in the laboratory, the sole purpose of obtaining chromaticity coordinates of the targets under sunlight conditions is to determine the biasing effect of the solar illuminant. In other words, to what degree does the sun degrade the inherent color of the targets? For example, at low sun angles the distribution of the solar illuminant increases appreciably at the red end of the spectrum, casting a reddish hue on the terrain. Colorimetric field measurement of, say, the white target will indicate the magnitude of this color shift and will permit the interpreter of multispectral imagery to correct the viewer illumination by that amount. This will be discussed later in the chapter.

These two sets of chromaticity coordinates (laboratory and field) should be measured *each* time a flight test is made; naturally, the field measurements will be taken throughout the photographic day in order to study the color bias introduced by *different* sun angles during the photo mission. Although colorimetric laboratory and field calibration of the ground reference panels will give a clear indication of the apparent color shift (this shift will be evidenced in the photography), such data tells nothing regarding the change in solar spectral distribution.

One may recall from Chapter 3 that any set of chromaticity coordinates (x, y, Y) can result from an infinite number of spectrophotometric curves. It is essential, therefore, that one ascertain those spectral regions which are affected by the solar illuminant. This may be conveniently done by measuring the white target spectral distribution both in the laboratory and in the field. As with the colorimetric laboratory procedure, an NBS standard illuminant A source and a regulated power supply is essential for the laboratory spectrophotometric calibration. The source-to-target and target-to-spectrophotometer (or spectroradiometer) distances and angles are set up according to the NBS source specification. Also, photodetectors contained within the spectroradiometer do not have a constant response as a function of wavelength and the spectroradiometer must itself be calibrated against a pure white reflectance standard of, say, magnesium oxide or barium sulfate. The calibration procedure includes setting the spectroradiometer and the source on an optical bench in order to maintain the precise alignment and distance between the spectroradiometer, the standard plate, and the source as specified by NBS.

Assuming that the standard plate is 100 percent reflective throughout the spectrum and that the angle between the source and the normal to the plate (see Figure 39), as well as the angle between the normal and the detector is small, the response of the spectroradiometer with wavelength can be determined. For example, suppose at 550 nm, the illuminant A source has an output of 60 microwatts per cm squared according to NBS. If the spectroradiometer measures only 40 mw/cm^2/nm after the light is reflected off the white standard, then any data measured at 550 nm must be corrected by

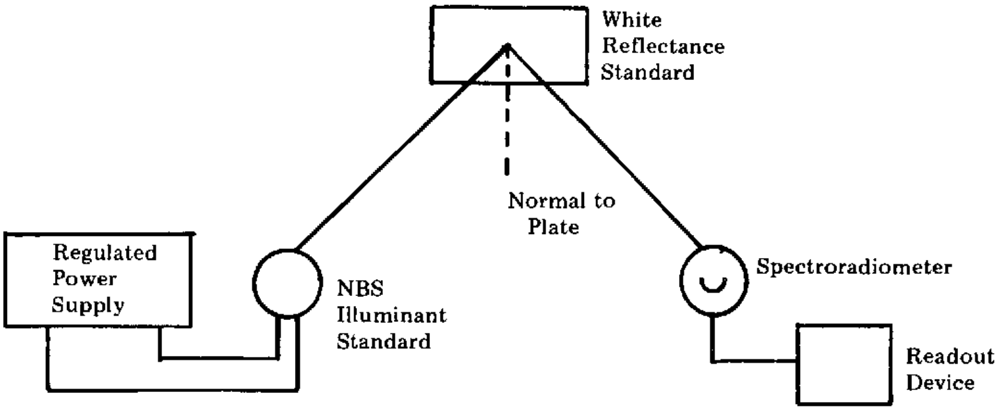


Figure 39. Laboratory set-up to measure spectroradiometer spectral response.

multiplying it by 1.5. A spectroradiometric correction curve can be generated for the entire spectral region under consideration by plotting the correction factors, $C\lambda$, along the y axis, and the wavelength along the x axis as shown in Figure 40.

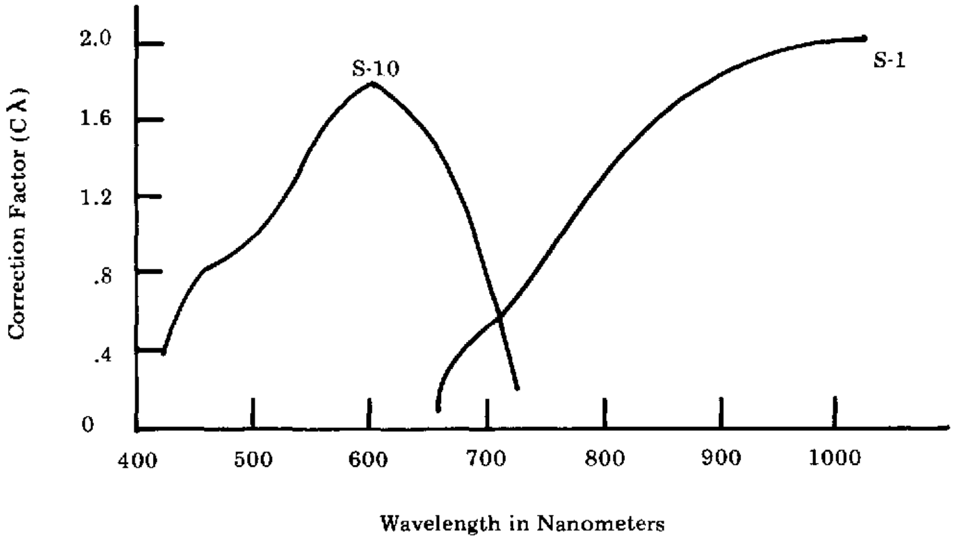


Figure 40. Correction factors for visible and near infrared photomultipliers.

Returning to the spectroradiometer calibration of the white target panel, the standard magnesium oxide plate is replaced by the ground reference panel and the procedure outlined above is repeated. That is, the spectroradiometer measures the reflectance of the target illuminated by the standard sources. This data is then multiplied by the correction factors illustrated in Figure 40.

Let the NBS lamp output at any wavelength be $L\lambda$, the spectroradiometer measurement at any wavelength be $S\lambda$, and the correction factor at any wavelength be $C\lambda$. Then,

$$C\lambda\,(s\lambda) = L\lambda\,(\rho\lambda)$$

where $p\lambda$ is the target reflectance at λ, or:

$$\rho\lambda = \frac{C\lambda\,(S\lambda)}{L\lambda}$$

The values of ρ for each wavelength become the laboratory spectroradiometer calibration of the white panel.

The field spectroradiometric data is obtained in the same fashion, except sunlight is now the illuminant. Although it may be interesting to measure the spectrophotometric properties of each reference panel, the large volumes of data make this impractical in most cases. From a statistical viewpoint it is far better to measure the white panel ten times, than each of the ten targets only once. The correct use and interpretation of these laboratory and field calibrations will now be discussed.

4.2 Effective Use of Reference Targets and Their Calibration

The ground reference panels are used in the taking, processing, and viewing of multispectral photography in order to determine:

- The correct exposure ratio between the multispectral bands.
- The corrections necessary when printing the positive images in order to produce satisfactory transparencies for the additive color viewer.
- The correct hue, brightness, and saturation of the multispectral additive color images for optimal interpretation of the scene.

Without the use of at least the gray scale standard, the tasks described above would become tediously difficult to perform with any degree of accuracy or repeatability.

4.2.1 Exposure Determination

Multispectral photography has the advantage over subtractive films in that the exposure of each record can be varied individually. Once selected, the exposures of each record will vary only if changes are made in any one of the following:

- the camera lens transmission
- the selection of different camera filters
- the use of a different emulsion
- the spectral distribution of the solar illuminant

Prior to flight, all of the above should be invariant with the exception of the illuminant so that it is possible to photometrically calibrate the camera and generate a set of pre-selected f/number differences between the records.

The first step in this process consists of establishing an exposure criteria based upon the reflectance of objects in the scene. The following are given as examples of this exposure relationship:

- that the photographic exposure be identical for each lens-filter-film combination,
- that the blue image have 2.5 times the exposure of the green, while the infrared have ½ the green exposure, etc.

When the exposure ratios have been established, the set of f/numbers corresponding to these ratios are determined in the following way:

- place the set of gray scale ground panels out of doors beyond the hyperfocal distance of the camera lenses,
- place the desired film in camera and the selected filters over the lenses,
- use a standard brightness meter or photometer to measure incoming solar illuminant,
- expose film at *each* f/number for every lens; that is, set each lens at f/2.5 and expose; reset lenses to f/5.6 and expose; repeat for all f/numbers. This should take only a few minutes to complete,
- remove filters from camera,
- measure incoming solar radiation with each individual filter in front of the photometer; record the data,
- after processing the film, examine the gray panels on the film, select those f/numbers (one for each record) which yield the gray scale density ratios required to fulfil your exposure

criteria. For example, suppose for equal exposure of the gray scale on each record, the following f/numbers are selected as shown in Table VII.

			Photometer Measurements Through Filters	
Record #	Filter #	f/Number	Pre-Flight	At Flight
1	A	8	200	
2	B	2.5	80	
3	C	5.6	160	
4	D	4	100	

Table VII

— The data is xeroxed and taken into the field during the flight test and the solar illumination is again measured using the same photometer and a duplicate set of selected camera filters. The last column of Table VII may now be filled in. Suppose the data is:

			Photometer Measurements Through Filters	
Record #	Filter #	f/Number	Pre-Flight	At Flight
1	A	8	200	220
2	B	2.5	80	120
3	C	5.6	160	120
4	D	4	100	100

Obviously, the pre-defined f/numbers will not yield the expected results due to a shift in the illuminant quality. Changes in the f/number or insertion of neutral density filters behind the colored camera filters will make the camera expose correctly. To determine the corrections necessary, we divide the pre-flight data by the at flight data, or:

Record #1 $\frac{200}{220}$ = Negligible Shift

Record #2 $\frac{80}{120}$ = -1/2 Stop

Record #3 $\frac{160}{120}$ = +1/2 Stop

Record #4 $\frac{100}{100}$ = No Change

This new data is relayed to the aircraft via ground-to-air communication so that the photographer can insert the appropriate N.D. filters behind the spectral filters.

It is not always possible to possess two sets of every camera filter (one for the sensor and a second for the photometer). The more practical method is to eliminate the photometer and to employ the spectroradiometer which is already required for the in situ spectral stdies of target reflectances. Instead of placing a filter over the collecting aperture, the total illumination is measured at a few points covering the transmission bands of each filter (naturally the same spectroradiometer would have to be employed to obtain both the pre-flight and the at flight data.) The resulting measurements will be valid as long as: (1) the measurements are taken from the white target, the reflectance of which is already known, and (2) the reflectance of the white target is measured at the same wavelengths when taking pre-flight and at flight data. Since,

Reflected Energy (R) = Incident Energy (I) x Target Reflectance (ρ) then,

$$I = R/\rho \qquad \text{Equation 4-1}$$

where: R is the reflected energy measured with the spectroradiometer in the field
ρ is the inherent target reflectance measured in the laboratory

The question arises as to which wavelengths are to be selected for an evaluation of (I) in the previous equation. Each filter in a multispectral camera possesses a peak wavelength and half bandwidth points, as shown in Figure 41. The peak wavelength is that value of λ at which the percent transmission of the filter is a maximum, while the ½ bandwidth points are those upper and lower values of λ for which the transmission is ½ of the peak transmission.

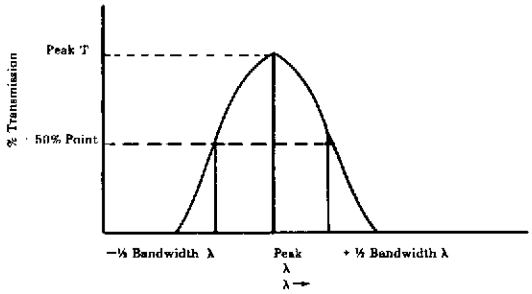


Figure 41. Definition of peak wavelength and ½ bandpass wavelength.

If, for example, four filters were chosen so that their transmission characteristics are similar to those of 42, then the wavelengths at which I is measured, both prior to and during the flight test, are shown along the x-axis and are recorded in Table VIII. At the time of pre-flight calibration, the

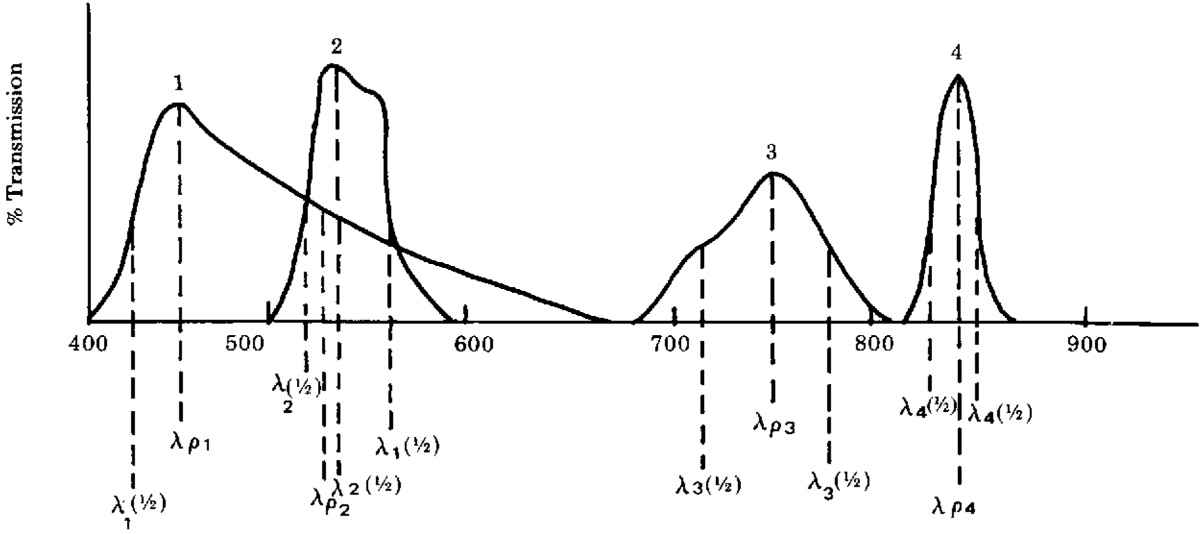


Figure 42. Peak and ½ bandwidth wavelength of four multispectral filters.

	Pre-Flight Illumination							
Record #	1		2		3		4	
	λ	I	λ	I	λ	I	λ	I
-1/2 λ	425 nm	( )	515 nm	( )	715 nm	( )	835 nm	( )
Peak λ	450 nm	( )	535 nm	( )	755 nm	( )	850 nm	( )
+1/2 λ	525 nm	( )	567 nm	( )	780 nm	( )	859 nm	( )

values of R for the wavelengths shown are measured and substituted into equation 4-1 to obtain the I's. That is,

$$\frac{R_{(-1/2\lambda)}}{P_{(-1/2\lambda)}} = I_{(-1/2\lambda)}$$

$$\frac{R_{(\lambda)}}{P_{(\lambda)}} = I_{(\lambda)}$$

$$\frac{R_{(+1/2\lambda)}}{P_{(+1/2\lambda)}} = I_{(+1/2\lambda)}$$

Each column of I's is then averaged to indicate the amount of solar energy incident in the particular spectral band. A similar set of data is obtained during the flight and the ratios between the pre-flight illumination and the at flight illumination are handled in the same way as for the photometer measurements.

Using this procedure, the pre-defined exposure ratios will always be adhered to, regardless of any changes in the quality of the illuminating solar energy which may occur on the day of flight.

4.2.2 Exposure and Processing Corrections

It will be shown in Section 7.3 that sensitometric step wedges must be placed on the leading and trailing edges of all rolls of film to maintain processing control. There is, however, for practical purposes, no substitute for a step wedge in the scene and the calibrated ground reference panels (gray scales) serve this purpose. By placing the ground targets somewhere around the middle of the flight line, it is not particularly inconvenient to overfly them several times in a single roll of film.

Although the ground target sensitometric wedges of each multispectral record are developed together for the same length of time, their gammas or the slopes of their characteristic curves will not be the same. Gamma depends not only upon the emulsion type and processing conditions, but also upon the spectral characteristics of the exposing radiation.

After processing the negative multispectral records and measuring the densities of the target panels on each, a set of characteristic curves possessing different gammas similar to those of Figure 43 are generated. These negative photographs must then be printed in positive transparency form for final recombination in the additive color viewer. If no correction for gamma is made in this printing stage, the higher wavelength multispectral photographs will predominate in the final viewer presentation. To eliminate this difficulty, the shapes of the characteristic curves for *each* record must be made *identical*. That is, the relationship between scene brightness range and density range must be be the same for each multispectral record as illustrated in Figure 44. This may be accomplished by a tone reproduction analysis (presented in Chapter 8) and four such reproduction diagrams must be generated — one for each multispectral record. The camera flare curve is constant for each record and

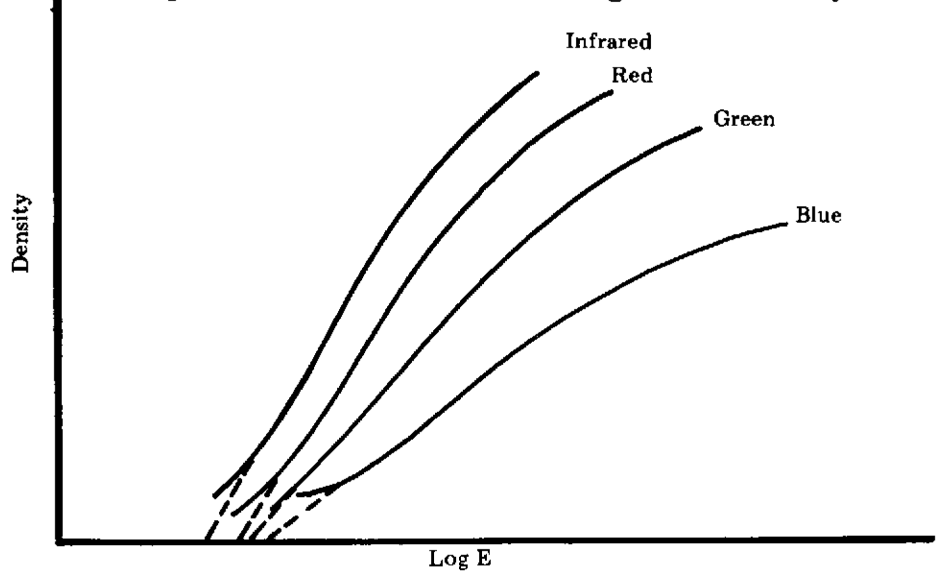


Figure 43. Gamma depends upon the wavelength of the exposing radiation.

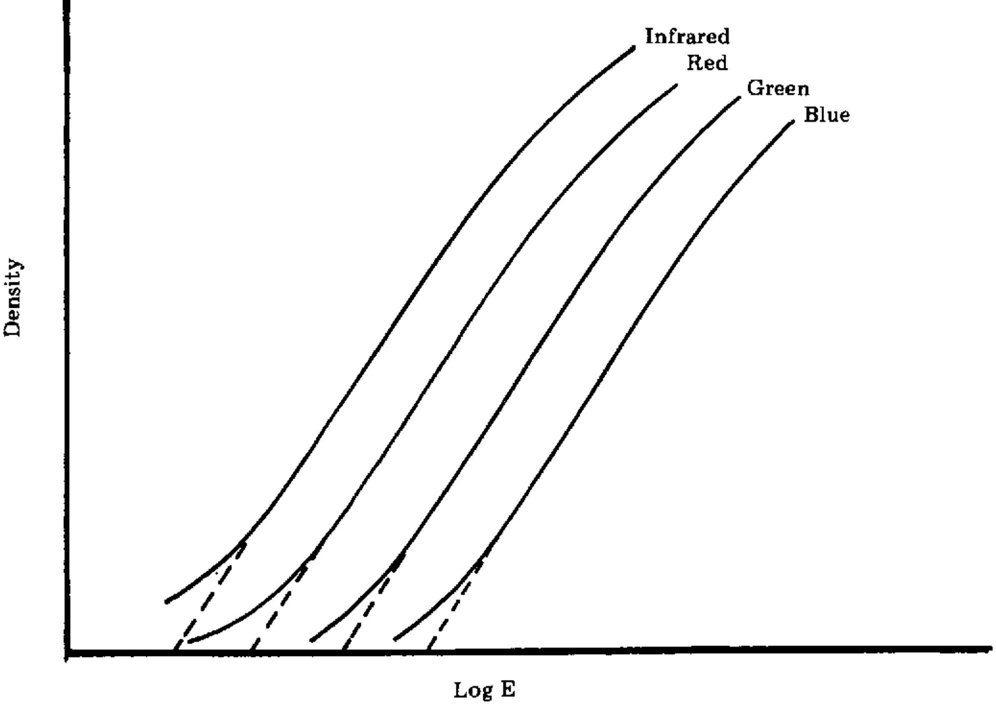


Figure 44. Gamma may be corrected in printing of the positive multispectral transparencies.

is plotted in the first quadrant of the tone reproduction figure. The characteristic curves for the negative material (one for each record) are different, as shown in Figure 43; these curves are plotted in quadrant II. In addition, acceptable multispectral positive images must possess the following characteristics:

- low minimum density
- highest possible gamma consistent with the scene brightness range of the subject.

These two conditions allow one to predict the optimal shape of the final reproduction shown in quadrant IV. This curve is identical for each multispectral photograph in a single frame. By extending the lines from quadrant II and IV to intersect in quadrant III, the characteristic curve of the positive material is obtained. That is, the shape of the H&D curve of quadrant III indicates the correct exposure and processing gamma of the positive material necessary for optimal reproduction of the scene. Since the shapes of the curves of Figure 43 are all different, the final exposure and gamma for the positive material will be different for all records. In summation, correct tone reproduction for positive multispectral imagery is produced by drawing four tone reproduction diagrams (one for each multispectral record) and filling in the quadrants as follows:

- drawing the camera flare curve in quadrant I of each diagram (this curve is constant),
- drawing the final desired reproduction curve in quadrant IV of each diagram (this curve is constant),
- drawing the characteristic curves for the multispectral negatives from the data contained in Figure 43 (this data changes for each wavelength band),
- generating the required H&D curve for the positive material in quadrant III of each diagram (this data changes for each multispectral record).

4.2.3 Color Correction of the Final Imagery

The use of standard gray scale and color targets in the scene is required for correct camera exposure and positive printing.

Suppose now that both multispectral additive and tri-pack subtractive imagery are flown over a test area containing the standard targets and that the white panel has laboratory CIE coordinates of (.33, .33, 80%) and field CIE coordinates of (.40, .30, 70%). Assume that photographic imagery of the white panel was obtained during the time when the chromaticity coordinates were measured and that perfect color reproductions of the scene resulted. The chromaticity coordinates measured from either the additive presentation or the color film would be (.40, .30, 70%). We already know that these coordinates are incorrect; however, by transforming (.40, .30, 70%) into (.33, .33, 80%) we will then have the truly correct color presentation of the scene. In an additive color viewer with controlled hue, brightness, and saturation, this transformation is rather simple to accomplish using a colorimeter equipped with a fiber optic probe. One merely adjusts the three parameters of color while measuring the chromaticity coordinate of, say, the white target until the desired (.33, .33, 80%) is obtained. On any other roll of film, on any other day, one merely adjusts the viewer until the white target again has the same coordinates. All other images will then have the correct color regardless of atmospheric effects, time of day, secondary reflectors, etc. This is particularly advantageous since photographic tests of the same types of ground objects are often flown over a period of days under widely varying solar illumination conditions. Also, once the desired photographic color characteristics of the ground objects have been established, they should be maintained. In other words, if a certain object has a color Q associated with it in one photo, it is desirable that it *always* remains the same regardless of the day or time. Measurement from standard panels in the scene greatly facilitates this.

While correction for tone and color balance in *color negative* materials is a rather complicated procedure (see Chapter 2), the known color of standard targets in the scene provides for a quantitative assessment of the compensations required in printing. Little or nothing can be done to correct a poorly exposed *reversal* transparency unless an internegative is made.

4.3 Ground Truth

To accurately interpret a photograph not only in terms of its general content and obvious characteristics, but also in terms of its most subtle density and color changes is the primary task of those engaged in remote sensing. Through the medium of photographic imagery, one attempts to assign to certain density and color effects, an environmental phenomena or cause present on the ground. Remote sensing looks beyond the obvious in a photograph, obtaining quantitative density and color data contained therein. The final step, of course, is to accurately demonstrate that such density and color measurements do, in fact, correlate with the conditions of the environment.

Natural terrain objects (unlike man-made) do not usually possess a consistent spectral distribution. Although the *basic* shape of the spectroradiometric curve may appear constant, there exist subtle color changes which depend upon the age of the object, its exact composition, the environmental conditions in which it exists and many more. In order to accurately interpret remote sensing imagery, it is necessary to provide a set of "keys" giving examples of typical terrain objects under varying conditions of the environment. These keys take the form of ground truth data, color and spectroradiometric measurements, and associated imagery over the ground truth area.

The site selected for ground truth analysis should possess the following characteristics:

- It should be small enough in area to be investigated rather thoroughly by a ground truth team.
- It should contain most of the objects under investigation and preferably a sufficient number of specimens for statistical sampling.
- Optimally, it should contain similar objects under different sets of environmental conditions. It is sometimes possible to artificially alter the environmental conditions of some specimens (e.g., irrigating some areas or artifically fertilizing several samples, etc.).
- The area selected for ground truth should be sufficiently isolated so that it remains undisturbed by the rest of humanity. (One classical example of this: a group of foresters had selected a site, taken extensive ground truth, overflown the area, and found some discrepancies in the imagery. They returned to the site for a double check only to find that most of the forested area had been cut down for Christmas trees!).

Ground truth should be collected as near to the time of flight as possible since the physical appearance and spectral reflectance of some objects change appreciably at certain times of the year. Ground truth is then annotated onto black-and-white prints of the area, preferably exposed at low altitude for clarity.

A set of sample data sheets for ground truth collection are included at the end of this chapter. They will, no doubt, have to be modified depending upon the particular characteristics of the test site, time of year, and the photographic mission objective. Nevertheless much of the physical description ground truth targets can easily be obtained prior to the measurement of reflectance spectra. As much data as possible should be filled out on the ground truth sheets, so that the crews equipped with these forms and an aerial photo of the area can concentrate their efforts on reflectance measurements and the immediate environmental factors which will influence that data.

Each ground truth team should consist of at least two people to measure reflectance and a third (familiar with the targets - for example, a forester, hydrologist, agronomist) to record the remainder of the data and to select samples for laboratory analysis.

For the sake of accuracy, it is advantageous if those who collect the data also reduce and analyze it. Ground truth teams are a good deal more careful in the selection of samples and the measurement of field data if they are made aware that they will be responsible for the test results and any conclusions drawn from them.

In addition to the incidence and reflectance spectroradiometric instrumentation discussed previously, the collection of adequate ground truth requires little in the way of auxiliary equipment. Properly labeled vials for laboratory samples, as well as a Polaroid color camera to photograph the targets, are essential. These photos, taken from the direction of the spectroradiometer, can be easily attached to the data sheets for future reference on exact target size, location, sun angle, etc.

4.4 Summary

- Quantitative analysis of color imagery necessitates placing standard panels in the scene, collecting complete ground truth, and making provision to color correct the photographic results.
- Ground targets should be diffused and the gray scale should exhibit flat spectral distribution over the visible-near infrared wavelength regions.
- Four color and six gray targets are considered the minimum number of ground panels necessary for quantitative analysis of film.
- Colorimetric and spectroradiometric calibration of ground targets should be made both in laboratory and in the field.
- Laboratory illuminant for calibration of targets must be an NBS standard.
- Exposure ratios between spectral bands are determined from in situ reflectance spectra of objects in scene.
- Different gammas on each multispectral negative record must be corrected for in the printing stage.
- Tone reproduction analysis will indicate requirements of the positive multispectral records so that gammas will match.
- Ground truth permits one to relate the color effect on the film with an environmental cause.

Agricultural Ground Truth Data Sheet

Date: ____________________ Field Designation: ____________________

Time: ____________________ Owner: ____________________

Weather: By:

Physical Description:

Size of Field: ____ x ____ or ____ acres Photo # ____________

General Soil Types: ____________________

Species or Cover: ____________________

Variety: ____________________

*Population: ____________________ plants/acre

*Row Width: ____________________

*Row Directions: ____________________

*applicable for row crops

Agricultural Data:

Planting/seeding date: ____________________

Planting Technique: ____________________

Flowering Date: ____________ % Cover: ________ Height: ____________

Heading/Tasseling Date: ____________ % Cover: ________ Height: ____________

Maturity Date ____________ % Cover: ________ Height: ____________

Anticipated Harvesting Date: ____________________

Plant Vigor: ____________________

Previous Rainfall: Date: ____________ Light ______ Medium ______ Heavy ______

Soil Moisture: ____________________

Treatment (fertilization, cultivation, etc.)

Type	Date

Spectral Reflectance Data:

Time: Start ____________ End ____________

Instrument (Incidence): ____________ Sun to crop angle: ____________

Instrument (Reflectance): ____________ Crop to SR angle: ____________

(Append data and reflectance curves on next sheet)

Figure 45

Geologic Ground Truth Data Sheet

Date: ______________________ Site Designation: ______________________
Time: ______________________ Owner: ______________________
Weather: ______________________ By: ______________________

Physical Description:

Area within Site: ______________________ Photo # ______________________
General Soil Types: ______________________
Ground Cover: ______________________
Target #: ______________ General Target Classification: ______________
Check Those Applicable:
Welded: ________ Non-Welded: ________ Vitric: ________ Volcanic: ________
Rubble: ________ Outcrop: ________ Soil: ________ Type: ________
Weathered: ________ Crystalline: ________ Sample Taken: Yes ___ No ________
Group Classification: ______________________
Target Size: ______________________

Laboratory Mineralization Tests:

Date: ______________________
Test Performed: ______________________
Target Composition: ______________________

____

____

____

Spectral Reflectance Data:

Time: Start ______________ End ______________
Sun to Target Angle: ______________________
Target to SR Angle: ______________________
Instrument (Incidence): ______________________
Instrument (Reflectance): ______________________
(Append data and reflectance curves on next page)

Figure 46

Hydrological and Oceanographic Ground Truth Data Sheet

Date: ______________________ Site Designation: ______________________
Time: ______________________ U.S.C.G. Chart #: ______________________
Weather: ______________________ By: ______________________

Physical Description:

Photo No.: ______________________
Location (referenced to land): ______________________

Tide: In ______________________ Out ______________________
Currents: Yes ____ No ____ Direction: __________ Speed: __________
Channel: ______________________ Bay: ______________________
Wind Speed: ______________________ Wind Direction: ______________________
Bottom Depth: ______________________
Water Temperature: ______________________
Salinity: ______________________
Presence of Injected Effluents: ______________________ Location: ______________________
Water Samples Taken: Yes ______________________ No ______________________
Depth: ______________________ Number: ______________________
Depth: ______________________ Number: ______________________
Depth: ______________________ Number: ______________________
Depth: ______________________ Number: ______________________
Depth: ______________________ Number: ______________________

Laboratory Analysis of Samples:

Date: ______________________ Type of Test: ______________________

Depth	#Refractile/cc	# /cc	# /cc	# /cc	# /cc	# /cc	Total #
ft							
ft							
ft							
ft							

Spectral Transmission Data:

Time: Start ______________________ End ______________________
Depth: ______________________
Instrument (Incidence): ______________________
Instrument (Reflectance): ______________________
(Append data and reflectance curves on next page)

Firgure 47

Forestry Ground Truth Data Sheet

Date:
Time:
Weather:

Site Designation:
Owner:
By:

Physical Description:

Area Within Site: Photo #:
General Soil Type:
Ground Cover: Species:
Variety:
Population: trees/acre
Target Description:
Height: Plant Vigor:
Density: Soil Moisture:
Crown Size: Previous Rain:
Maturity:
Needle Samples Taken: Soil Sample Taken:

Laboratory Analysis of Samples:

Date:
Type of Test:

Minerals in Soil	Mined	Minerals in Ash (ppm)

Spectral Reflectance Data:

Time: Start End
Sun to Target Angle:
Target to SR Angle:
Instrument (Incidence):
Instrument (Reflectance):

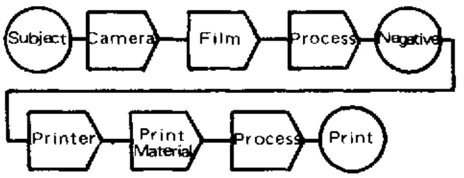
(Append data and reflectance curves on next page)

Firgure 48

CHAPTER 5

SENSITOMETRY

The photographic process consists of a rather complex chain which links the photographed subject with the final positive, suitable for detailed interpretation. A block diagram of the process is shown in Figure 49. It should be noted that the sensor (camera) plays a rather minor role in the overall scheme, while the emulsion selected and the conditions used each affect the final photographic product. A black-and-white photographic process must only simulate or reproduce the tonal values of a scene. Full color photography, however, must be capable of reproducing the multitude of hues in a scene, as well as their brightness or tone. For pictorial photography, it is usually sufficient for the user to decide either that he likes or does not like the photo reproduction of his scene. However, for more subtle photographic applications (such as earth resources study), the aerial photographer is particularly concerned with how well the resultant image density or color relates to the conditions present in the scene.



Block Diagram of a Photographic Process

Figure 49. Block Diagram of a Photographic Process

By way of illustration, consider the problem of interpreting density changes on black-and-white aerial photographs. Assume that a flight line is photographed at 9:00 AM, 12:00 noon, and 4:00 PM, and the film is processed immediately after each run. An examination of the three film strips shows that different densities are present for the same image depending upon the hour of the flight. Question — what caused the different densities? Several possibilities come to mind:

1. The effect of differences in solar sun angle and illumination, since the red component of the sun increased in the early morning and late afternoon.
2. The effect of late afternoon haze conditions caused by industrial smoke in the area. Although this wasn't a factor at 9:00 AM, it could have been at 4:00 PM.
3. The effect of altering the camera exposure since less exposure was required at noon when the sun was brightest.
4. Any effect which might have been caused by using three separate rolls of film, since films characteristically differ from roll to roll.
5. Reuse of the same developer which might have produced different densities of each roll of film since developer loses its strength with use.

The most important question the photographer might ask is — "If I fly another area tomorrow with the same types of objects in the scene, how can I interpret the resulting image densities accurately when I get different densities on today's flights over the same area?". The problem appears, at first glance, to have no solution. However, by applying certain measurements to the photographic process, a relationship can be made between the ground object and its image density on the film regardless of solar conditions, atmospheric haze, film or processing conditions. This is accomplished through the use of accurate and continued sensitometric control.

Sensitometry is a science fundamentally concerned with the measurement and evaluation of the response of a photographic emulsion to radiant energy. It involves five distinct tasks:

- The exposure of the film to a source of illumination whose radiant energy is known.
- The development of the film under accurately controlled conditions of temperature, time, chemical strength, solution agitation, and drying.
- The use of a density standard such as a "density step tablet".
- The precise measurement of the image densities produced on the film.
- The interpretation of these measurements.

Sensitometry is primarily used to established correct development time so that accurate and reproduceable imagery results. However, such techniques are also employed to determine the speed, gamma, and exposure latitudes of film and to investigate the maximum contrast in a scene which a film can record correctly.

5.1 Sensitometric Test Procedures

5.1.1 Exposure

Photographic films are coated with a gelatin emulsion into which are embedded tiny crystals of silver halide. Some of these crystals are made to be more sensitive to different kinds of light — for example,x-ray, infrared, ultraviolet, visible, etc. Exposure of these crystals to light, for a given length of time, causes the formation of a latent image on the film. The exposed silver halide is then converted to metallic silver by an agent in the developer. The extent of conversion to metallic silver (density) is a function of the amount of light exposing the crystals (photographic exposure) and is given by:

$$E = It$$

where I is the intensity of the light source and t is the exposure time in seconds. For visible light, the source intensity is measured in units of meter-candles resulting in a photographic exposure expressed in meter-candle seconds. When processed, the final image will have a density which may be related to its photographic exposure. Sufficient variation in this photographic exposure (E) will produce an entire range of film densities from clear to opaque.

The light source employed for the sensitometric evaluation of a film should have the same characteristic as the source under which the actual imagery will be taken. In the case of aerial photography, sunlight is used as the scene illuminant; a flash tube with a color temperature of 5400°K, which approximates sunlight, is employed for sensitometric tests since this light source fulfills the following conditions:

- its spectral distribution covers the entire photographic region from 360 nm to 920 nm,
- it maintains an almost constant intensity over long periods of time.

The sensitometric characteristics of a film are determined by analyzing the densities which result from various exposures. Since the photographic exposue (E) is related to both intensity (I) and time (t), it is necessary to alter either the radiant output of the light source or the exposure time. This is performed by an instrument which is used to expose photographic materials for testing and evaluation and is known as a sensitometer (shown schematically in Figure 50). It consists basically of a light source, either a shutter or timer to control exposure, and a density step wedge (Figure 51) to control the illumination falling onto the film. The step wedge is made by exposing between 11 and 21 steps to a lighted field in succession; generally, the densities of the steps are such that they produce film exposures which increase as the log of .15, ranging from 0 density to 4.0 density. Although they can be made in the photo lab, gray scale step wedges are commercially available from, say, Eastman Kodak Company and are supplied with precise density measurements of each step.

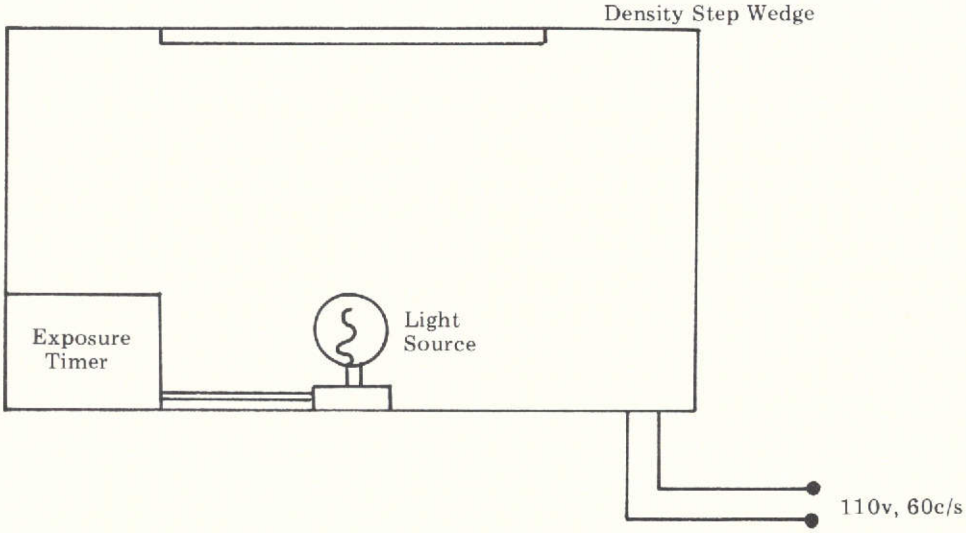


Figure 50. Schematic of sensitometer showing basic components.

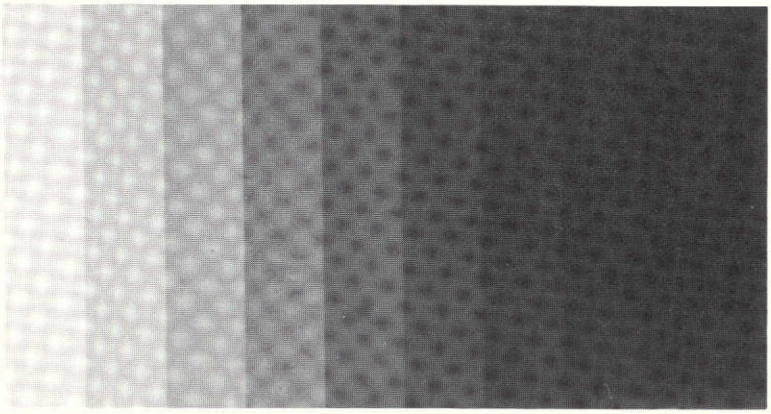


Figure 51. Density step wedge.

5.1.2 Sensitometers

The E.G.&G. Mark VI Sensitometer, a self-contained unit housed in a molded plastic case, is solidly constructed and conveniently sized for inclusion in any modern darkroom arrangement. Four operating controls (On-Off toggle and 10^{-2}, 10^{-3}, and 10^{-4} exposure time selector switches) are located on the front panel of the instrument. A fourth control (trigger switch) is located under the hinged cover platen at the top of the instrument. Triggering is accomplished either by depressing the platen or remotely through a receptacle on the right of the base. (A suitable contactor and leads must be provided.)

The sensitometer operates on standard 115 V, 60-cycle, a/c power. A built-in voltage regulator circuit prevents change in light output with line-voltage fluctuations from 95 V to 130 V. The time constants of the three different RC circuits provide three precise duration flashes at three different energy levels. The highest output, approximately 3000 meter-candle-seconds (M.C.S.) is obtained from the 10^{-3} sec circuit. The 10^{-2} and 10^{-4} sec circuits deliver approximately 600 and 55 M.C.S., respectively.

The complete Mark VI system consists of the sensitometer, a gray-scale box, flashtube shield, two variable-area filters, and a Kodak No. 2 photographic 21-step tablet. The gray-scale box, which is inserted into the body cavity under the platen of the instrument, provides the exposure platform upon which the film undergoing test is exposed. The variable area filters (3-line and 19-line), which are inserted between the flashtube shield and the gray-scale box, allow the user to balance the light output. The 3-line and 19-line filters, which can be considered equivalent to ND 1.70 and ND 1.0 filters, are used to reduce the light output of the 10^{-3} and 10^{-4} sec circuits, respectively, to that of the 10^{-4} sec circuit. The reduction of the light output of the three circuits can be useful in studying film characteristics and exposure reciprocity effects. The step tablet is supplied as an exposure modulator. Neutral density filters, which must be cut to fit into the body cavity, can be used to reduce the light output of the individual circuits to suit the needs of the specific film undergoing test. Neutral density filters (Kodak Wratten 96 series, or equivalent) can be obtained from most photographic supply houses.

The Mark VI, because of the precise duration and repeatability of its 10^{-2}, 10^{-3}, and 10^{-4} circuit outputs, is an ideal tool for exposure reciprocity effects studies. With this instrument, the reciprocity effect for a given film can be demonstrated simply by generating separate characteristic curves using each of the separate exposure time settings with the required variable area compensator in place. Since the total light output in the film plane is nearly constant for all circuits when the compensators are inserted, each film would be receiving the same exposure as the product of the different intensity-time factors. Any shift in the resultant characteristic curve from that achieved at the standard exposure duration would indicate the effect of exposure reciprocity.

The Herrnfeld Sensitometer finds its primary use in the motion picture industry for testing of the film samples and processing control. This instrument uses tungsten light source; the exposure time can be varied by changing the width of a slit adjacent to the sample.

The Eastman Kodak Processing Control Sensitometer incorporates a tungsten light source, a motor driven shutter at a fixed time of 1/5th or 1/10th second, and can be obtained with various step tablets (optical wedges). As the name of this instrument implies, it is not offered as a precision instrument nor does it conform completely to the present standard. It is useful for the exposure of samples intended to be employed in tests of processing equipment control. It also is widely used as the basis of tests for comparing different films, developers, etc.

There are several alternatives to the use of a sensitometer if none is available to expose the wedge onto the film. First, a standard transmission type step wedge may be procured and either contact printed or projection printed (using an enlarger) onto the strip of test film. Although this method is much less accurate and reproducible than exposing the wedge in a sensitometer, it is, nevertheless, far superior to having no step wedge exposed on the film at all. The second method of obtaining sensitometric data on film is to purchase or rent large step wedge panels which may be placed in the scene and photographed with the camera. Data Corporation in Dayton, Ohio, leases such canvas panels (up to 100' x 100' square) and their nominal reflectances are 4%, 8%, 16%, 32%, and 64%. When placed in a line, these panels act as a modified step wedge on the film as may be seen in Figure 52.

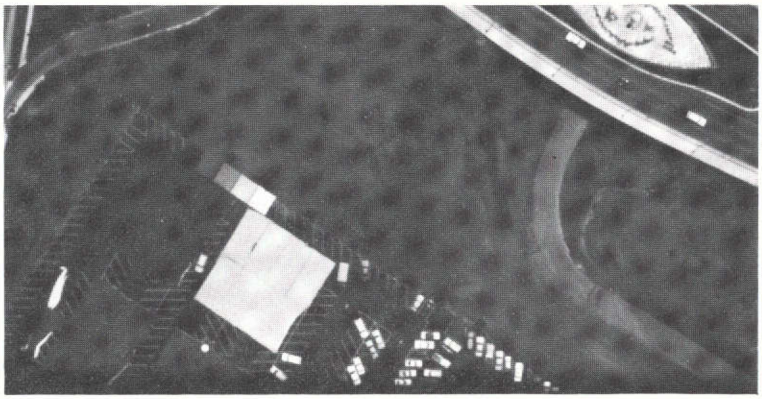


Figure 52. Large gray scale and color panels placed in the scene.

5.1.3 Processing

When the density step wedge has been properly exposed, the film is then processed. It is absolutely essential that the development be reproducible and that it be uniform throughout the test strip. Processing standards must be established and include such factors as:

- Developer strength
- Control of agitation
- Washing and fixing control
- Drying factors

A typical darkroom arrangement for developing black-and-white films is shown in Figure 53. Five trays are used and the processing takes place from left to right in the following sequence:

1. Development of image.
2. First wash to remove residual development chemicals from the emulsion.
3. Film rinsed in short stop to quickly stop the development process from continuing. Note: development continues to this point.
4. Clearing of the film in the hypo to remove the unexposed silver from the emulsion.
5. Final wash to remove residual chemicals.
6. Option of using photo flow to assure even drying of the film.

Several steps preparatory to processing should be taken to assure accurate reproduction of the test strip step wedges. Development may be performed using either tanks or trays, although roll film is more easily processed in tanks or automatic processing machines. Nevertheless, all containers should be thoroughly cleaned to remove any residue of old chemicals which might have accumulated. Prior to mixing the developer and hypo, an analysis of the water used should be made; often there exists excessive quantities of sand in the tap water, especially when the water is supplied from an artesian well. This sand, although in suspension, tends to stick to the gelatin emulsions producing a "sandy" feel and appearance on the film. Filters which may be set into the water line to remove sand and excess chemicals from the water are commercially available.

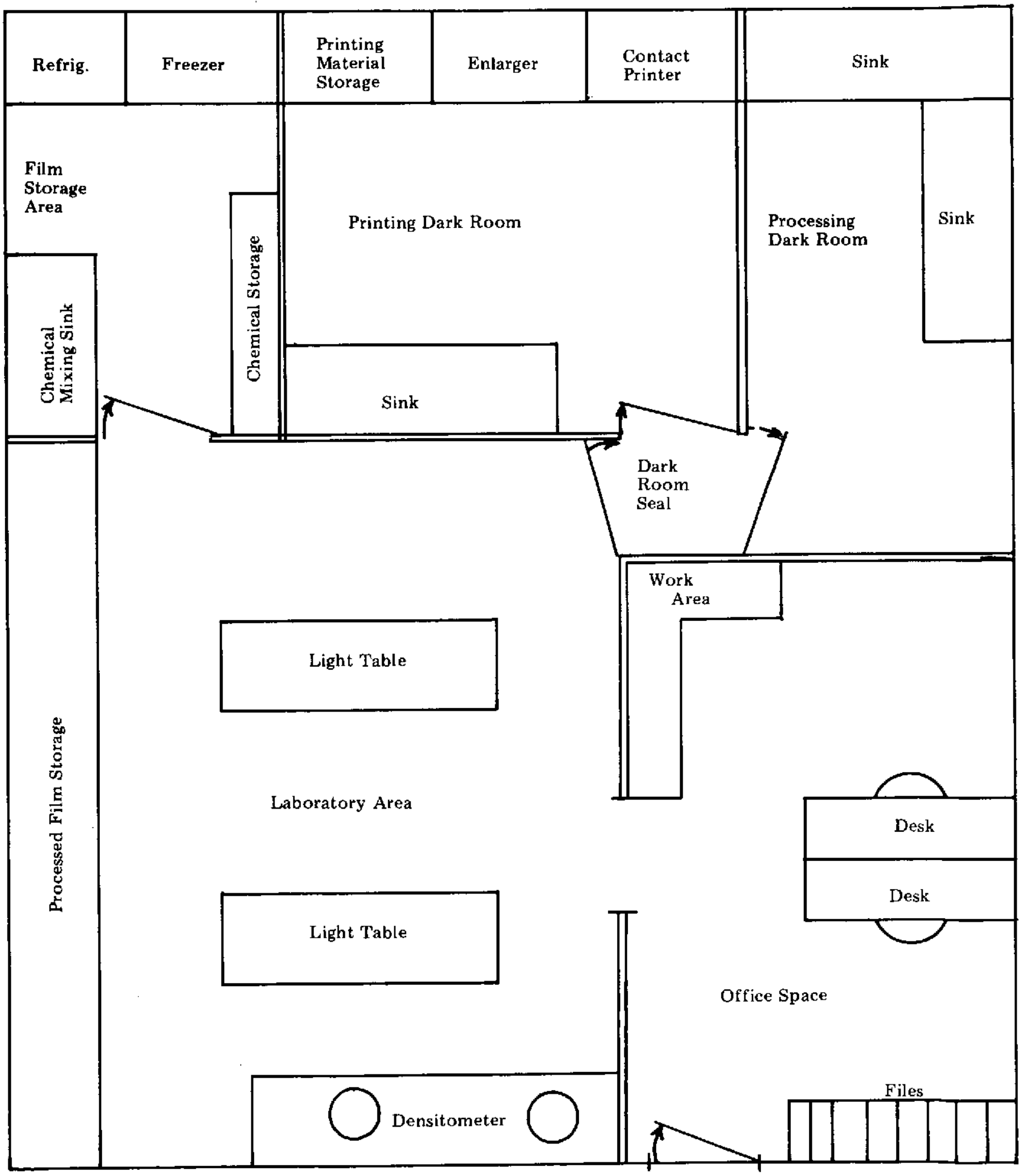


Figure 53. Layout of a precision darkroom and adjoining area.

The type of developer used to process a particular film is specified by the film manufacturer and requires mixing just prior to use. Mixing directions for both developer and fixer must be followed exactly if repeatable results are to be expected. Making small batches of the developer and fixer is often more economical than mixing large volumes at once since the solutions oxidize with time and have a shelf life of only about one to two months depending upon the chemical composition of the developer.

Once the chemicals have been mixed, they must be cooled before using; in most cases processing temperatures are specified to be 68°F (20°C), although some materials may be processed at temperatures as high as 85°F. The time-temperature charts discussed in Chapter 6 will show that the resultant film density is a function of processing, chemistry, temperature, and time. Therefore, the temperature of the processing solutions should be kept accurate to ±½°F, especially when developing color films. The simplest method of maintaining a constant solution temperature is to place all tanks and trays in a large water bath. The temperature of this water jacket can be controlled by use of a thermostatically regulated immersion heater. It is often helpful to keep the darkroom temperature at the same level as the processing solutions; heat transfer into and out of the water jacket will then be minimized.

Developing solutions can generally be used to process a considerable amount of film over appreciable lengths of time. Some agents such as D-76 may become dark and cloudy with use but this does not impair their effectiveness. The developer does, however, become slower in action due to (1) the depletion of the developing chemicals in solution, and (2) the accumulation of processing by-products in the developer. Hence, the length of time in which a film is processed must be increased gradually as the developer strength decreases with use. The best control over development strength can be maintained by exposing a sensitometric step wedge on a strip of film and processing it in a new batch of developer. This strip then becomes the standard. As the developer is depleted, several other wedges are exposed, processed for different lengths of time, and compared to the standard. The wedge which best matches the standard represents the new development time. In large scale processing or when economy is desirable, replenishing agents may be added to the depleted developer in order to (1) substantially increase its life, and (2) to make increases in processing time unnecessary.

A note of caution: extreme care should be taken so that the developer does not become contaminated by other solutions such as fixer, short stop, etc.

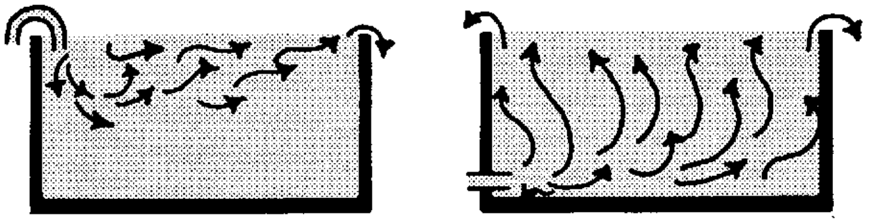
5.1.4 Fixing and Washing

After the development process, both the metallic silver image and the undeveloped silver halide (the areas not exposed to light) still exist together in the emulsion. Also the undeveloped silver halide is still sensitive to light. In order to remove the unwanted silver halide from the gelatin and to stabilize the image, the film undergoes a process called fixing. Fixers such as sodium thiosulfate convert the unwanted silver to a water soluble form permitting them to be "washed out" of the emulsion. Hardening agents are added to the fixer in order to make the gelatin tough and resistant to scratches.

There has been much discussion concerning the length of time for which a film should be fixed. Generally, the maximum time is thirty minutes, although with commercially available rapid fixer the time has been reduced to about four minutes. As the unwanted silver goes into solution, the film loses its opacity and clears. A good rule of thumb is to fix the film twice as long as it takes to clear. A note of caution: do not turn on darkroom lights until the film has cleared. When in doubt, it is better to wait another few minutes than to inadvertently expose the undeveloped silver to light. A few comments on fixers:

- A fixer will clear the film faster when the temperature of the solution is increased.
- Smaller grain films fix faster than large grain films.
- Thinner emulsions fix faster than thick emulsions.
- Fixer may be used in concentrations of 25-40 percent; follow manufacturer's directions for mixing and concentration.
- Do not use exhausted fixer; it produces staining, clearing is difficult, and the film requires more time for drying.
- Test fixer for exhaustion by employing a technique such as the potassium iodide precipitation test as follows:
    - 10 milliliters of 4% potassium iodide mixed with 100 milliliters of hypo to be tested.
    - Shake the solution.
    - If a yellow precipitate falls out, then the hypo is exhausted.

Having completed the fixing process, the film is thoroughly washed to prevent crystallization of any residual processing chemicals or dissolved silver on the film surface. The film should be washed for a time depending upon how long one wishes the film to last without staining. In general, 90% of the chemicals are removed from the film surface in five minutes; of the remaining 10%, 90% of these are removed in the next five minutes; of the remaining 1%, 90% of these are removed in the next five minutes, and so forth. Generally, films should be washed for at least thirty minutes to one hour for permanency. This time interval will differ depending upon the circulation rate and efficiency. Figure 54 below, shows two types of washing tanks, and if the poor design is employed, then the washing time must be at least doubled.



Poor wash-tank design. Note that the water is turbulent only near the top of the tank

Good wash-tank design, producing turbulence throughout the tank.

Figure 54. Two types of washing tanks for photographic film.

Some brief comments about washing:

- Washing time is decreased with an increase in the water bath temperature. This, however, will tend to soften the emulsion and extreme care must be taken that the film is not touched by anything which might cause the emulsion to peel. This includes the edges of other pieces of film in the tank.
- A hypo cleaning agent such as sodium sulfite will decrease the required washing time.
- Films fixed in a solution which lacks a hardening agent take more time to wash since an unhardened emulsion tends to hold more hypo than a hardened film.

Drying the film is the last step in the processing procedure. This should take place in an area with a relative humidity of about 65% and a temperature of about 68°F. Increasing the ambient room temperature will, of course, speed up the drying process. Nevertheless, too much heat will melt the emulsion or cause the outer gelatin layers to dry while those nearest to the base will still be damp. This condition may set-up stains within the emulsion and increase the graininess of the images. Sufficient air flow is essential to an even drying of the film and it follows that as the air circulation is increased, the drying time will be decreased. It is also helpful to squeegee the surface water from the film; this step (optional) must be done with extreme care lest scratching of the soft emulsion take place. One of the best film drying methods consists of hanging the film in a drying cabinet. Most of these units consist of electrical heaters and blowers which keep the air circulating. They are commercially available, do not take up much room, and are very helpful in keeping the water off the floor.

One further note: a darkroom can become a very sloppy place to work in. Chemicals splash, the film drips wet while being moved from tank to tank, and working under completely dark conditions amplifies this situation. Wipe all surfaces with a clean sponge or rag after processing of each batch of film. Chemicals left on surfaces can permanently stain or otherwise ruin darkroom equipment.

5.1.5 Processing Summary

The following procedure should be followed in order to accurately and repeatedly process both sensitometric step wedges and exposed imagery:

1. Select the developer and fixer to be used from the film manufacturer's recommendation. This information is supplied with the film.
2. Check the quality of the water supply, and, if necessary, use a filter to remove excess chemicals and suspended material.
3. Use tanks or trays depending upon the quality of film to be processed.
4. Clean all equipment prior to use, including:
   - Tanks or trays — four in all — for developer, developer wash, fixer, and final wash.
   - Solution mixing bottles.
   - Thermometer.
5. Mix developer and fixer EXACTLY according to the manufacturer's instructions.
6. Cool solutions prior to use.
7. Place tanks or trays in a water bath to maintain correct processing temperature.
8. Check solution temperatures just prior to developing.
9. Use a darkroom clock and preset the alarm for desired processing time.
10. Agitate tank or tray according to manufacturer's instructions.

5.2 Measurement of Sensitometric Data

As stated previously, the conversion of a latent image into a metallic silver deposit (density) on the film is related to the amount of light striking the film (exposure). The density of film is a measure of the transmission characteristics of the developed emulsion, while the density of paper is a measure of its reflectance properties. Hence, there exist two types of densities — transmission and reflection, each one requiring a different method of measurement. Only transmission densitometry will be considered here.

A processed photographic film is basically translucent and when light strikes it some of the light is absorbed, some is transmitted, and some is reflected. The transmission of a film is defined as the ratio of the light which passes through it to the total amount of light incident. That is,

$$\text{Transmission} = \frac{\text{Transmitted Light}}{\text{Incident Light}}$$

The extent of opaqueness due to metallic silver in the emulsion is called opacity and it is defined as the reciprocal of the transmission or:

$$\text{Opacity} = \frac{\text{Incident Light}}{\text{Transmitted Light}}$$

When the transmission of the emulsion becomes very small, the opacity becomes quite large and cumbersome to use. To simplify the situation, the density of film is used and is defined as the common logarithm of opacity:

$$\text{Density} = \text{lo}_{10}\ 0 \text{ opacity}$$

By way of illustrating the relationship between transmission, opacity, the following table is given:

TABLE IX
Relationship Between Transmission, Opacity, and Density

Transmission	1/2	1/4	1/8	1/16
Opacity	2	4	8	16
Density	.3	.6	.9	1.2

It should be noted that there are two distinct definitions of density which relate to the nature of photographic films. A beam of light passing through an emulsion is scattered in all directions by the silver particles as shown in Figure 55. When a narrow beam of light falls on the film sample and the densitometer collecting aperture or integrating sphere is placed sufficiently far away so that only the "paraxial" rays enter the sensing head, then the density measurements are said to be *specular* as shown in Figure 56.

Notice that only the rays which emerge almost perpendicular to the film are measured. *Diffuse* density can be measured in two ways. Figure 57 illustrates the case in which light from all angles falls onto an opal diffusing glass before passing through the film. The collecting sphere is placed sufficiently far away so that only the rays which are almost perpendicular to the film are measured. The second method of measuring diffuse density consists of focusing a narrow beam of light onto the emulsion and placing the collecting aperture in contact with the film. This situation is illustrated in Figure 58. As may be expected, the specular density will be higher than the diffuse density measured from the same film area. This is due to the fact that not as many rays of light enter the integrating sphere of the densitometer where it is placed away from the film. Specular density is difficult to measure because of the necessity of exact alignment between the incident light, the film, and the collecting aperture of the instrument.

because of the necessity of exact alignment between the incident light, the film, and the collecting aperture of the instrument.

Although most densitometers used today are electronic, direct reading instruments which measure diffuse density, both visual and electronic types will be discussed.

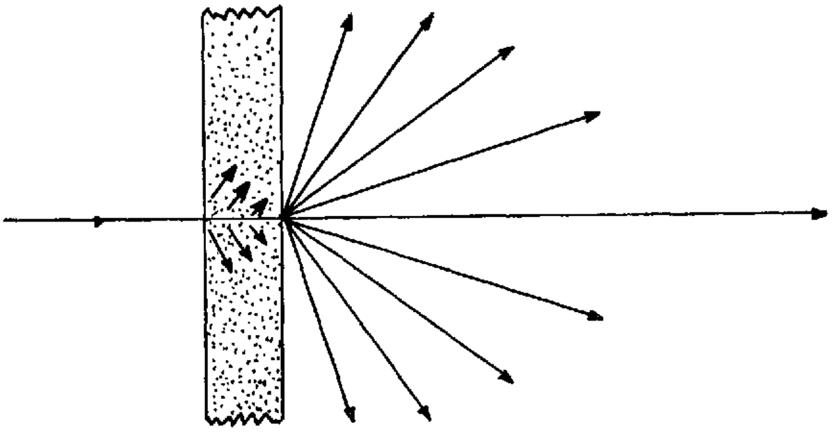


Figure 55. Scattering of light by silver particles within an emulsion.

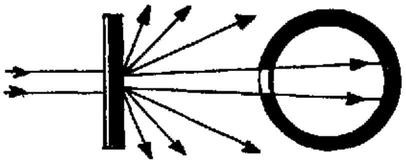


Figure 56. Measurement of specular density.

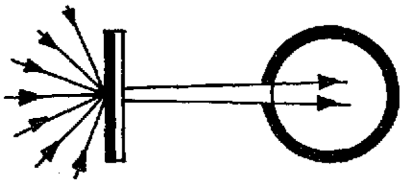


Figure 57. Measurement of diffuse density.

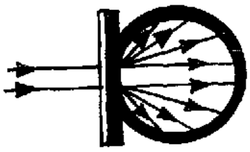
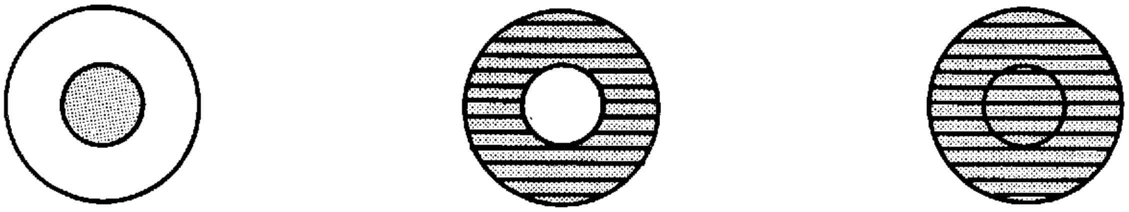


Figure 58. Second method of measuring diffuse density.

5.2.1 Densitometers

A visual densitometer is one which depends upon a visual comparison and evaluation of the film with a standard density. Although they are, in general, sufficiently reliable for most measurements, the great variable in the system is the human eye. Visual densitometers employ two adjacent fields of light; the first field of view contains the sample to be measured and the second contains a continuous density wedge. A knob on the face of the instrument controls the position of the wedge and indicates the amount of density in the second field of view which is required to create a visual match. The density of the sample is then read from the knob. Figure 59 illustrates two cases in which the film and standard densities do not match and one case in which they do.



Sample denser than standard

Sample lighter than standard

Matched densities between sample and standard

Figure 59. Densitometer fields showing their differences, as well as a good density match.

A schematic diagram of a visual densitometer is shown in Figure 60 below. Two identical light sources, S1 and S2, illuminate the sample (f) and density wedge (w) respectively. A circular mirror, M, with a hole in it directs the light from the wedge onto a diffuser, D. The illumination from the sample (f) passes through the hole in the mirror and is focussed in the center of the angular ring from the standard beam. A density match is made by moving the wedge.

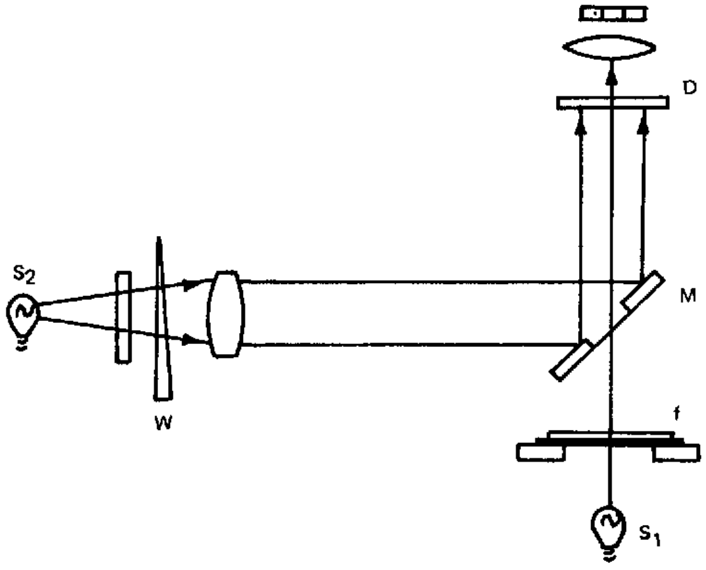


Figure 60. Double light source densitometer.

Another more accurate visual densitometer is shown in Figure 61. It is a well-known fact that the illumination from a light source decreases as a function of the square of the distance from it. That is,

$$I_d = \frac{I_0}{d^2}$$

where I_0 is the intensity of the light measured at a distance one foot from the source,

I_d is the illumination at a distance d from the light source. For example, if a source radiates 20 foot candles of light (I_0), then at a distance (d) two feet away, the light (I_d) is only five foot candles since:

$$I_d = \frac{20}{(2)^2} = 5$$

The densitometer shown in Figure 61 is based upon this principle and is known as an inverse square law instrument. As the light source, S, is moved to the left, the amount of light through the sample (f) is increased, while the amount of light in the comparison beam is decreased. Moving the light source to the right produces the opposite effect. The scale attached to the light source is calibrated according to the difference in the distance between the beams and reads directly in density.

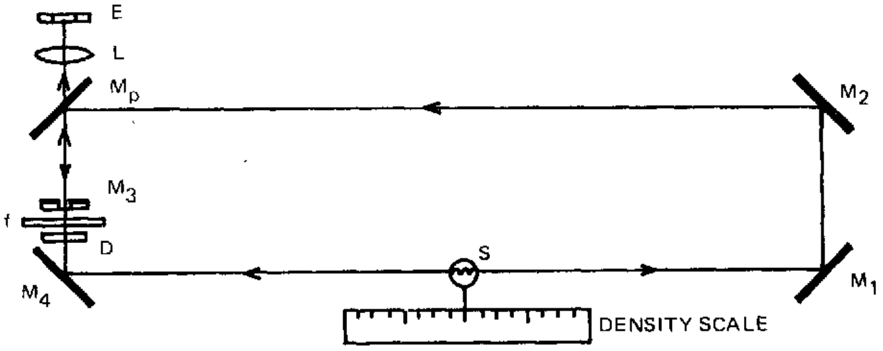


Figure 61. Inverse Square Law visual densitometer.

The sensitivity of the eye is such that the precision of the visual densitometer is limited to density differences of .005. Actually, the instruments are not even that precise, owing to eye fatigue which results in lower density discrimination. As a result, most visual densitometers have been replaced by photo-electric instruments. In addition to being able to measure density differences to about .0005 (ten times better than the visual densitometers), photo-electric units can make about sixty readings per minute compared to six readings per minute for the visual densitometer.

There are two common types of photo-electronic densitometers: direct reading and balancing or null. Figure 62 shows some of the components of a direct reading photo-electric densitometer. Referring to Figure 62 the illumination from the source is directed (by means of a lens) through a small aperture. This illumination then falls onto a photodetector, the electrical output of which is amplified and displayed on a meter calibrated in density units. When no film density is being measured, the light transmission through the aperture is 100 percent and the meter reads "zero" density. However, when a photographic emulsion is placed over the aperture, the amount of light reaching the photodetector is reduced by the opacity of the film and the meter reads the correct value of density directly.

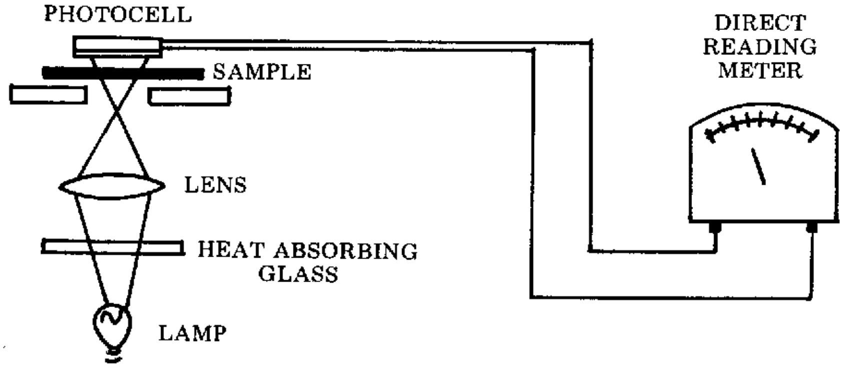


Figure 62. Basic components of a direct reading photoelectric densitometer.

Figure 63, below, shows a schematic of a null or balancing densitometer. This particular instrument separates the illumination into two light beams and the meter indicates whether or not there exists a balance between the two beams. When no film is placed over the aperture, the two beams are balanced and the meter reads zero density. When film is placed over the aperture, the beams are not balanced. The operator then brings the needle on the meter to the null position by moving the neutral density wedge and the film density is read from a calibrated scale on the wedge.

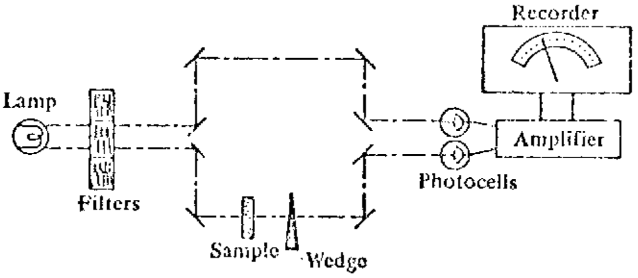


Figure 63. Null or balancing type densitometer.

Most densitometers have provision for measuring not only black-and-white densities, but also the color densities (red, green, and blue) which are associated with color films. The instruments contain a set of three filters (red, green, and blue) which may be successively inserted in front of the source to measure color density as follows. One of the color filters (say, green) is inserted into the light path and absorbs the red and blue components of the source. The photo detector then only "sees" the amount of green transmitted by the film which is read as a density. Without moving the film, the red and blue filters are placed into the light path and their densities are measured. The advantage of a color densitometer is that it gives an indication of both the density contained in each dye layer of a color film, as well as the composite density of all three layers (by removing any filters from the light path).

The Macbeth Quantalog Transmission Densitometer TD-102 has been developed to fill the need for an easy-to-operate, reliable, precision instrument for measuring the color and visual densities of materials. The readings taken with the TD-102 indicate diffuse transmission density, on the linear meter scale, with evenly spaced gradations. The total power consumed by the TD-102 is approximately 60 watts and the power transformer of the TD-102 has been designed for either 115 or 230 volt operation at power line frequencies of 50 and 60 cycles/second.

The electronic power supply of the TD-102 is self-regulated and hence is not affected by normal line voltage variations. However, line voltage variations will affect the stability of the energy radiated by the optical system's light source. Therefore, a voltage regulator must be used to prevent these fluctuations from causing reading errors. The instrument is equipped with a color filter turret which contains four filter positions. The filters installed are the Wratten #92 in the red, the #93 in the green, the #94 in the blue, and the #106 in the visual filter position. The linear 0 to 4.0 density scale is divided into 200 gradations, each equal to 0.02 density units. The circular stage diffuser has a brightness of approximately 100 foot lamberts. Circular apertures of 1mm, 2mm, and 3mm are supplied for measuring different size images.

The Itek recording densitometer, Model RD-2, is a compact, precision densitometer providing automatic readout and plotting of black-and-white film density. The instrument permits automatic plotting of characterisitic curves, scene density spread, or image density by means of a photometer system integrally coupled to a direct density readout and an automatic curve plotter. In addition, the unit can act as a precise spot reading and available as BCD electrical outputs.

The instrument provides density readout and plots from 0 to 4.0 ± 0.02 density unit accuracy. Film density can be measured continuously or at any point over a 5-inch long scan track of the sample by ½ millimeter wide collection aperture which energizes an all-solid state regulated, DC photometer. Density readings are repeatable to 0.005 density unit from scan to scan over the sample.

The reading station accommodates all film sizes in roll or chip form without film cutting or the use of film clamping platens, thus minimizing film handling and abrasion. Characteristic curves can be read and plotted from continuous or step density wedges in fifteen seconds for process control uses or in forty-five seconds for precision laboratory measurements by scan speed selection. A cross-hair reticle is provided to enable accurate positioning of the sample spot over the reading aperture during spot density reading. In addition to the aperture supplied (½ by 1½ millimeters), the unit can be provided with a variety of smaller apertures for specialized densitometric operations.

A digital readout meter which converts the analog voltage to a digital signal to operate the numeric display is installed in the RD-2. Terminals that are provided on the meter permit the digital signal to be tapped off for transmission directly to a computer or to computer terminal equipment.

When using the Tech/Ops color recording densitometer, three color filters and three corresponding pens are automatically selected during a single, forty-five second scanning cycle to provide a three-color plot of optical density along a 16mm or 35mm sample. The color recording densitometer contains an internal reference wedge for accuracy within ±0.01 density up to 2.0 density and within ± 0.02 density for the full 0 to 3.5 density range. The unit is calibrated for ASA fine-grain film. A differential speed control slows down the scanning speed when large density changes occur.

It is difficult to recommend one particular densitometer over another. The choice of a unit is dependent upon many factors: stability, price, work load, maintenance requirements, etc. In situations where the work load is high, an automatic densitometer might be worth the additional cost in order to obtain data which is recorded, punched on cards, or plotted automatically. Although visual densitometers are the most time consuming to use, they are very stable and may be employed in situations where the sensitometric work load is small.

5.2.2 Densitometer Operation

Once the choice of a densitometer has been made, the unit must produce repeatable results over long periods of time. The following precautions should be taken to assure this.

- Photo-electric densitometers require long warm-up times to reach stability. Therefore, the densitometer should be turned on and left on continuously, even when not in use. The lamp is turned off, except during use.
- Films should be handled only while wearing cotton gloves; particular care should be taken when handling calibrated step wedges to avoid scratches, fingermarks, dirt, etc.
- The densitometer must be zeroed prior to each set of measurements. This is accomplished by reading the density when there is no film in the gate. Should the density reading appear higher than zero or lower (off the scale), the "zero adjust" knob is turned until the density scale on the meter reads zero. A periodic check on this zero point should be made while taking density measurements.
- Some densitometers are supplied with apertures of various sizes (for example, 1mm, 2mm, and 3mm). Often the densitometer light source has two wattage ratings associated with it, one for the 1mm and 2mm apertures and the other for the 3mm aperture. A switch on the back of the densitometer is provided to select either the "high" or "low" beam depending upon the aperture used. Always check that the switch is in the correct position.
- A calibrated step wedge must be employed as a standard density scale. Checking the measured density readings from the densitometer with those measured densities supplied with the wedge gives a good indication of instrument performance and allows a density correction curve to be generated.

The design of data sheets to record and plot the sensitometric and densitometric measurements discussed in this chapter, as well as Chapter 6, are now given.

5.3 Design of Sensitometric Data Sheets

This section gives the required procedure and the data sheets used to analyze the results of sensitometric film testing. Some of the illustrations may require modification depending upon the specific instruments employed or user applications.

— Densitometer Correction Curve: The operational performance of densitometers is relatively constant over long periods of time. However, if the instrument exhibits some drift, it will become necessary to generate a correction curve so that the accurate measurement of density is still possible. Using the data sheet of Figure 64, the densities of a standard calibrated step wedge are copied directly from the wedge and recorded on the data sheet. Each step is then read on the densitometer in question and these measured densities are also recorded. The measured densities of the wedge are then plotted against the calibrated density values of each step. If no densitometer error exists, the resulting correction curve will be a straight line at 45° to the x axis. The curve will take some other shape if error is present in the instrument. To obtain accurate density values, one finds the measured density along the y axis, moves horizontally until reaching the correction curve, and reads the true density from the value along the x axis at that point.

— Relative log E Curve: The characteristic curve of a film may be plotted as either the density of the original vs. the density of the reproduction or as the step number of the original vs. the density of the reproduction. The x axis of Figure 65 shows both the step number and the density of the original calibrated step wedge. The densities of a 21-step tablet have increments of .15 density. Note that step #1 of the original wedge is located near the right side of the x axis while the #21 step is located near the left side.

— D log E (or Characteristic) Curve: The D log E curve is similar to the Relative log E curve, except that the common logarithm of the exposure must be determined. This is accomplished by (1) obtaining the sensitometer lamp output (in meter candles) from the manufacturer, (2) multiplying this value by the sensitometer exposure time, and (3) finding the common log of the result of (2). This produces the log of the sensitometer exposure. To find the log exposure of each step in the reproduced wedge, one merely subtracts the calibrated densities of the original wedge from the log of the sensitometer exposure. The y axis of the graph of Figure 66 can be expanded to accommodate a greater density scale if necessary, while the log E range shown along the x axis is generally sufficient.

— Time-Gamma Curve: Generally time-gamma and time-fog curves are plotted on a single graph together with a family of H&D curves showing the change in gamma with development. To construct these plots, identically exposed sensitometric wedges are processed at varying times for the same agitation and temperature. The H&D curve of each wedge is plotted on the same graph and labelled as to the time of development. Five such wedges give reliable results and three is definitely the minimum number required. After measuring the gamma of each curve, the values are plotted against development time in the corner of the large graph, as shown in Figure 67. Some increase in fog level may also exist as the gamma increased and this information can also be plotted against development time. The x axis of the small graph represents the development time, while the fog level density is shown on the left side y axis and the gamma on the right side y axis.

— Time-Temperature Chart: To plot a time-temperature chart, one requires at least two (2) time-gamma curves as shown above. One of these curves should be generated from a set of sensitometric wedges processed at 65°F and the second curve from a set of wedges processed at 75°F. Select a gamma value. From the 65°F time-gamma curve, determine the processing time necessary to achieve this gamma. Plot this point on the time-temperature chart of Figure 68. Determine the processing time at a temperature of 75°F necessary to achieve the same gamma and plot this second point. Connect the two points with a straight line and repeat the process for each gamma value of interest. Usually, the time-temperature curve is plotted on semi-log as shown in Figure 68.

5.4 Summary

- Sensitometry is the study of the response of a film emulsion to radiant energy.
- Sensitometry consists of the precise exposure, processing, and measurement of a film.
- Standard calibrated21-step wedges have nominal incremental density differences of .15.
- Precision processing involves exact control of chemical strength, temperature, agitation.
- Transmission of light is defined as the ratio of the light passing through a film to the total amount incident.
- Opacity is the reciprocal of transmission.
- Density is the common log of opacity.
- Specular density is always higher than diffuse density.

Figure 64

Densitometer Correction Curve

Densitometer: ____________________
Wedge #: ____________________

Data Read By: ________________________
Date: ________________________

Step No.	Calibrated Density	Measured Density
1		
2		
3		
4		
5		
6		
7		
8		
9		
10		

Step No.	Calibrated Density	Measured Density
11		
12		
13		
14		
15		
16		
17		
18		
19		
20		

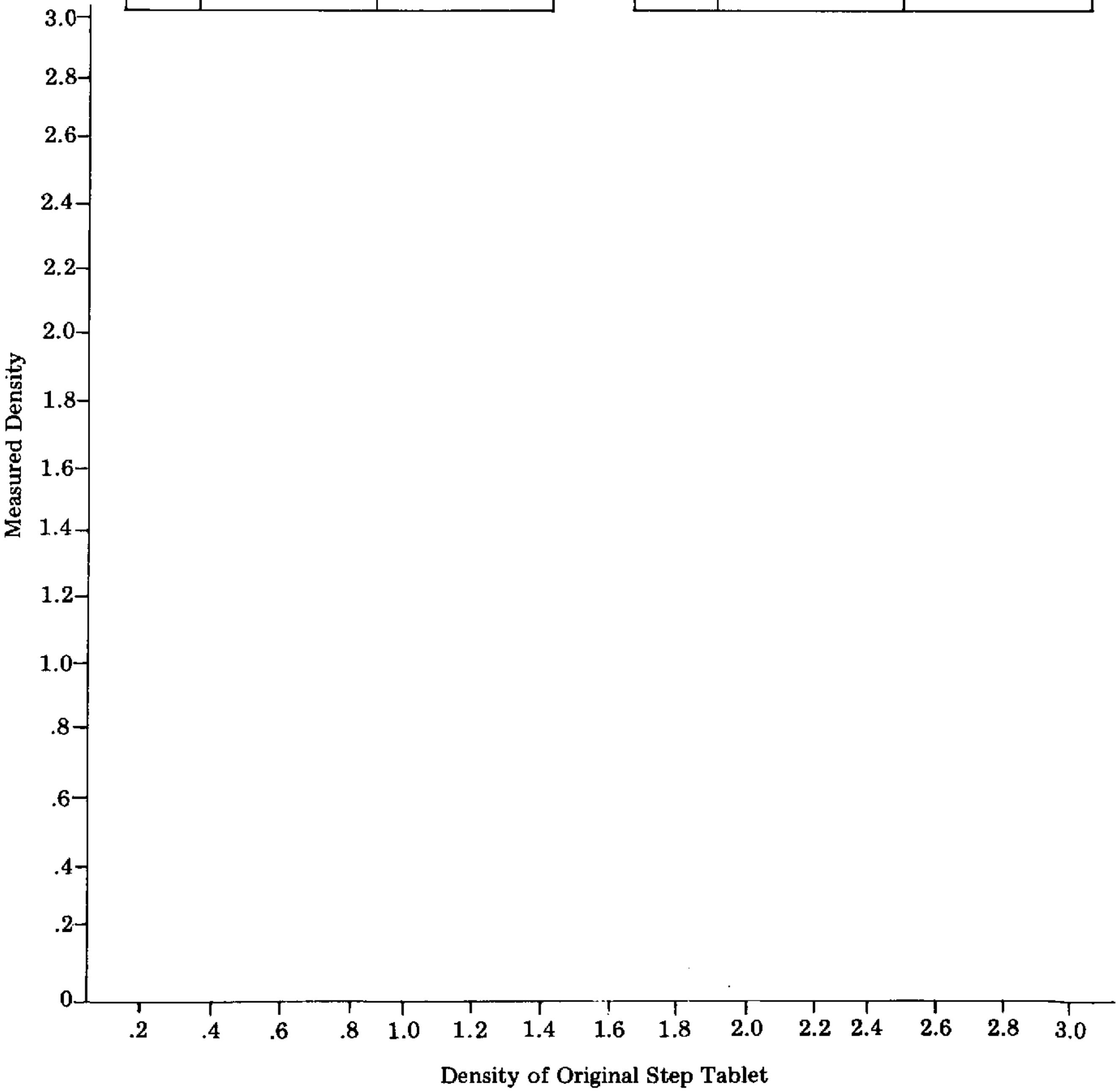


Figure 65

Relative D log E Curve

Film: ____________________
Developer: ____________________
Develop. Time: ____________________
Develop. Temp: ____________________
Agitation: ____________________

Step Wedge No.: ____________________
Sensitometer Exp.: ____________________
Data Read By: ____________________
Date: ____________________

Step No.	Calibrated Density	Measured Density
1		
2		
3		
4		
5		
6		
7		
8		
9		
10		

Step No.	Calibrated Density	Measured Density
11		
12		
13		
14		
15		
16		
17		
18		
19		
20		

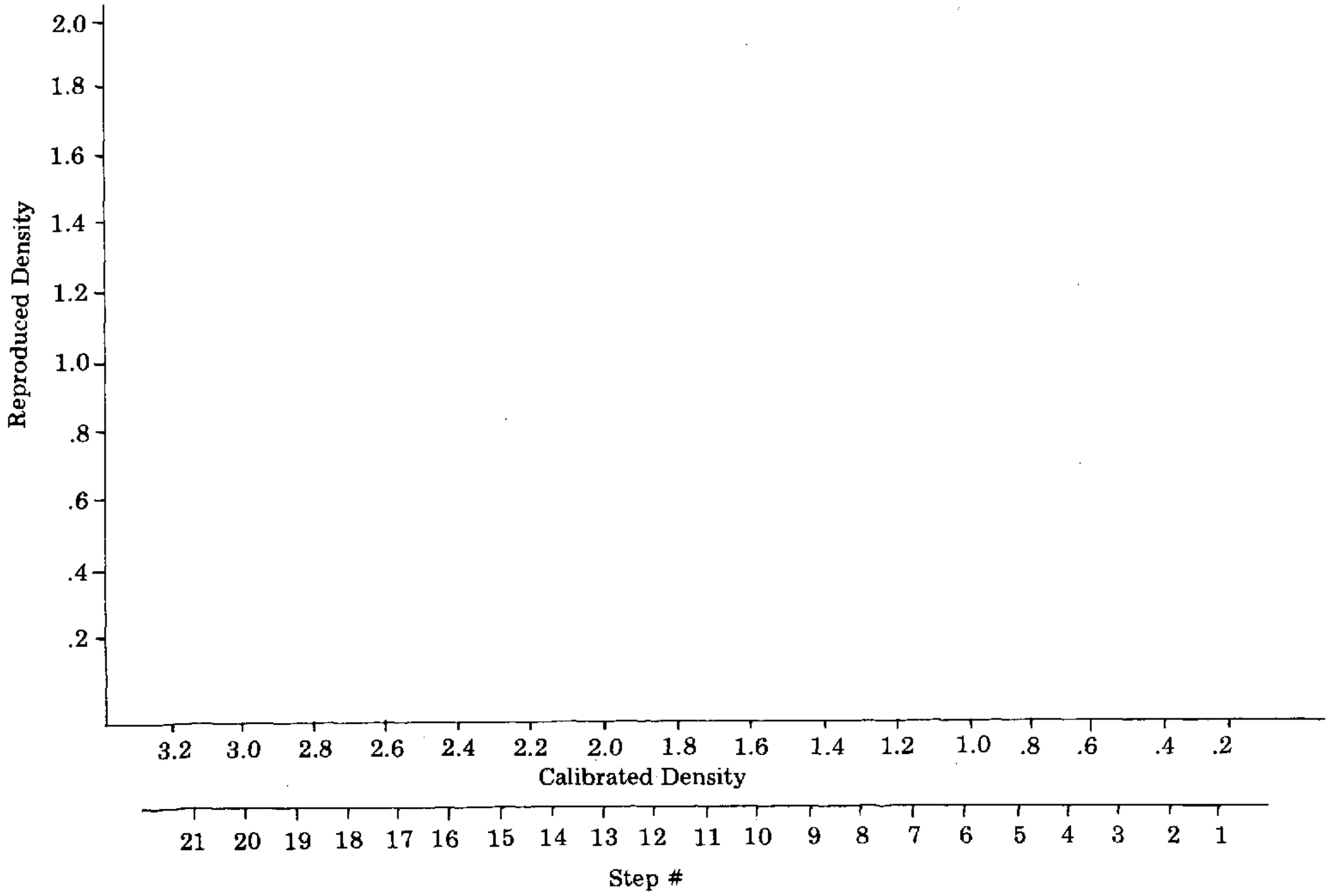


Figure 66

D log E (Characteristic) Curve

Film: ____________________
Developer: ____________________
Develop. Time: ____________________
Develop. Temp: ____________________
Agitation: ____________________

Step Wedge No.: ____________________
Sensitometer Exp.: ____________________
Data Read By: ____________________
Date: ____________________

Step No.	Calibrated Density	Measured Density
1		
2		
3		
4		
5		
6		
7		
8		
9		
10		

Step No.	Calibrated Density	Measured Density
11		
12		
13		
14		
15		
16		
17		
18		
19		
20		

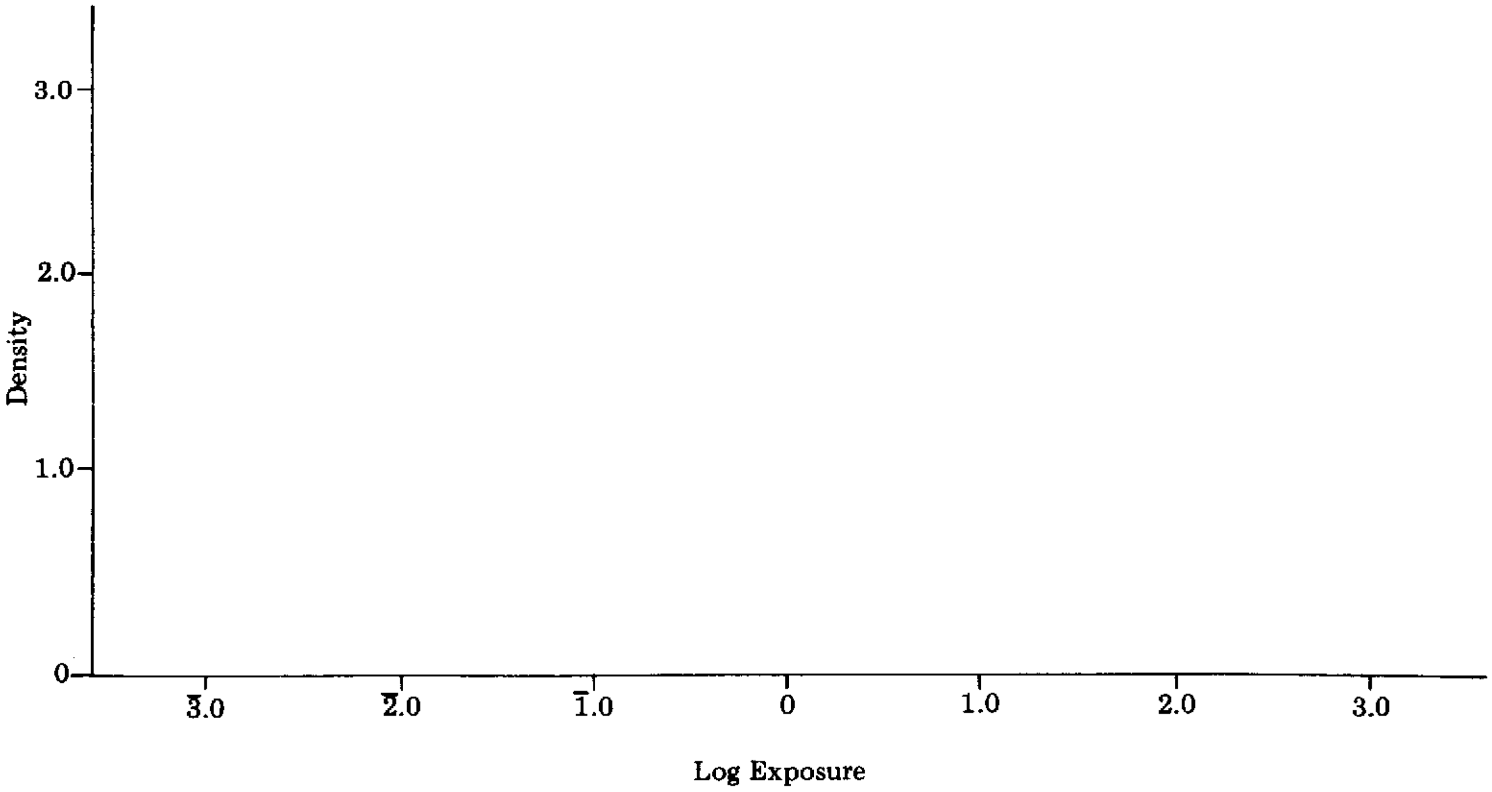


Figure 67

Time-Gamma, Time-Fog Curves

Film: ______________________

Developer: ______________________

Develop. Time: ______________________

Develop. Temp: ______________________

Agitation ______________________

Step Wedge No.: ______________________

Sensitometer Exp.: ______________________

Data Recorded By: ______________________

Date: ______________________

Wedge No.	Development Time	Resultant Gamma	Fog Density
1			
2			
3			
4			

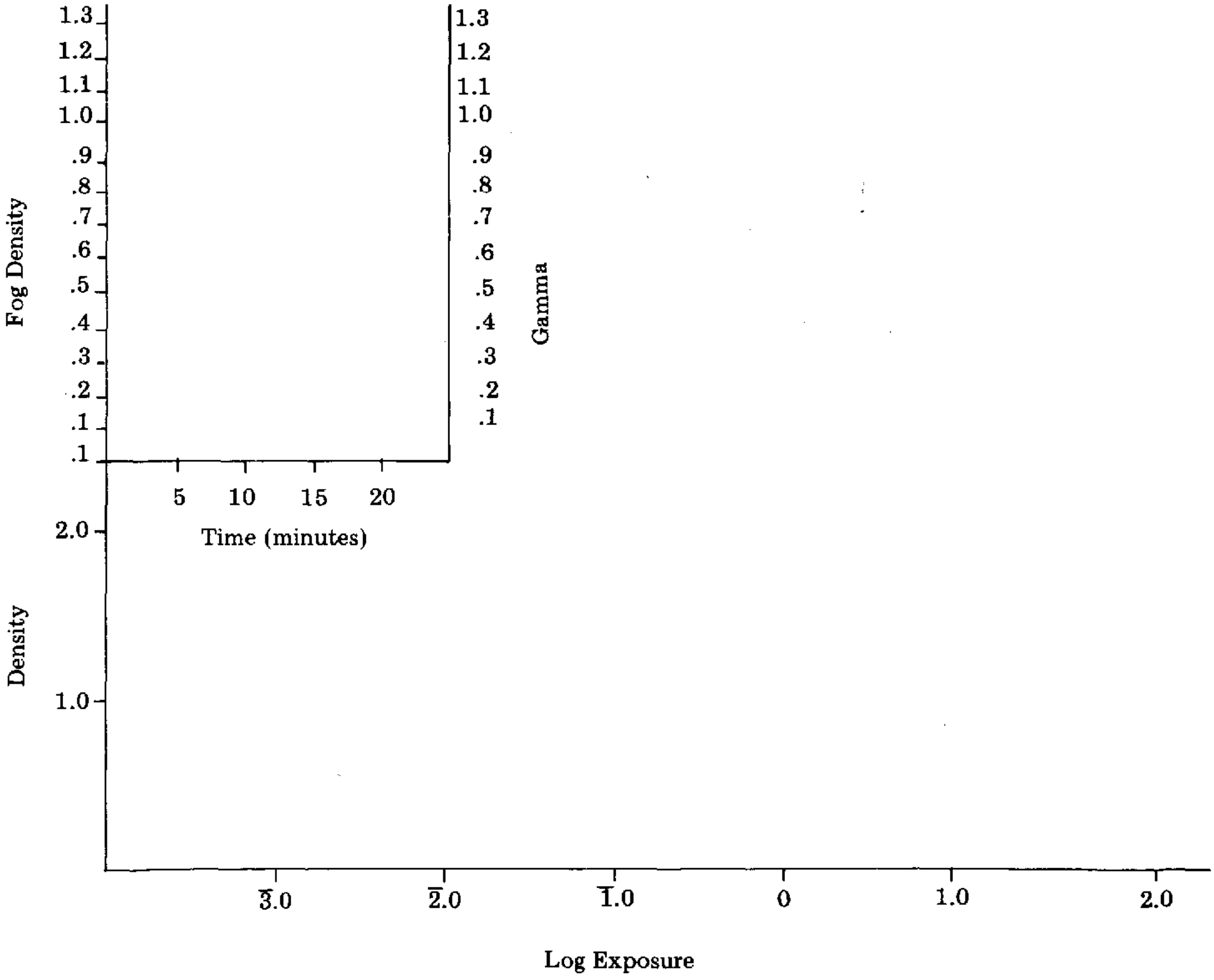


Figure 68

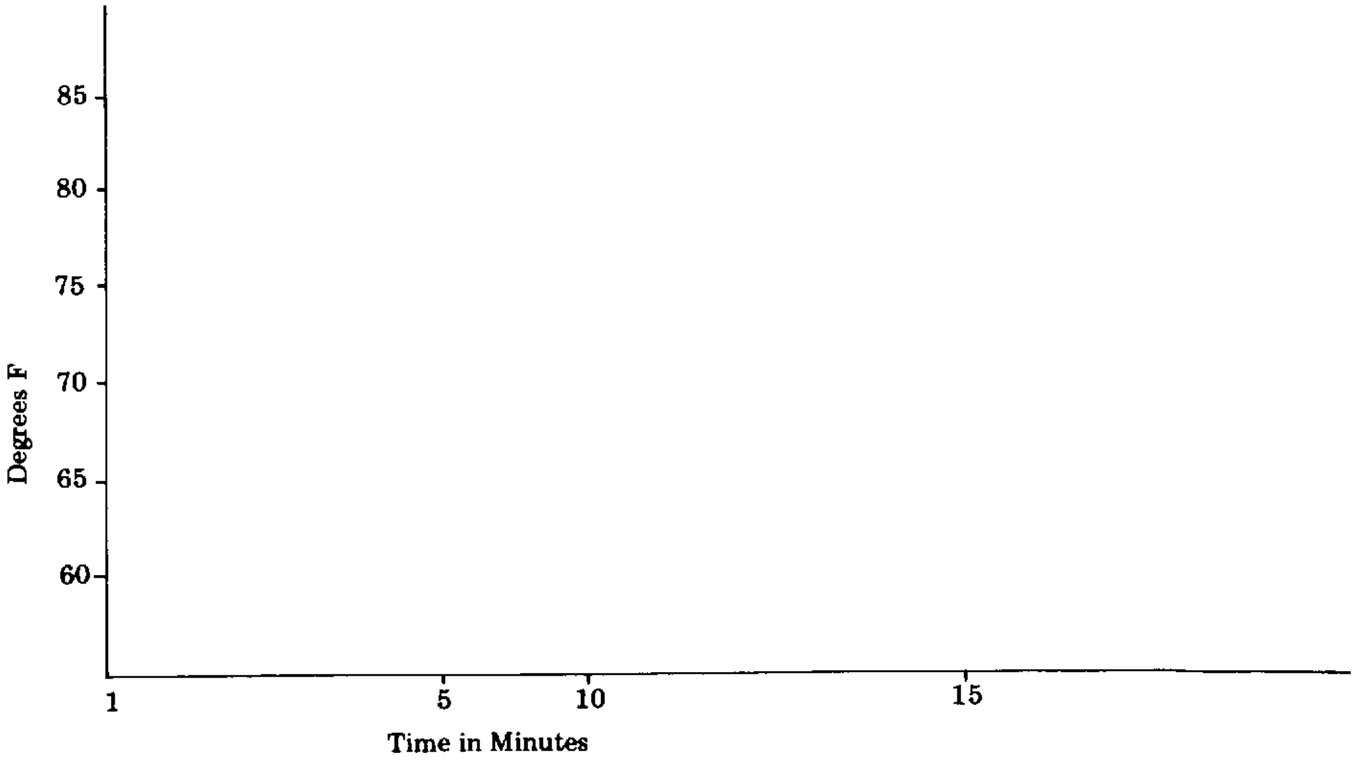
Time-Temperature Chart

Film: ____________________
Developer: ____________________
Develop. Time: ____________________
Develop. Temp: ____________________
Agitation: ____________________

Step Wedge No.: ______________
Sensitometer Exp.: ______________
Data Recorded By: ______________
Date: ______________

Temperature °F	
Time	Gamma

Temperature °F	
Time	Gamma



CHAPTER 6

SENSITOMETRIC DATA HANDLING

The complex interrelationship and dependency of the photographic variables of film, exposure, and processing schedules are such that a hit-and-miss approach to the process will rarely result in useful quantitative photographic data. With accurate sensitometric techniques, however, the complex photographic variables can be analyzed, both separately and scientifically. The precision and repeatability of an accurate sensitometer makes it possible to consider all aspects of the photographic process from the point of view of exact, controlled exposure. Film characteristics and the effects of processing conditions can thus be determined easily and precisely.

The primary function of sensitometry consists of the generation and interpretation of characteristic curves. These curves are established by exposing a piece of test film for a given length of time to a specific source of illumination which is attenuated by use of a density step wedge. Figure 69 shows the configuration of an E.G.&G. sensitometer and the following procedure is used to obtain sensitometric data from this unit:

1. Insert the necessary neutral density filter over the flashtube shield.
2. Make certain that the supporting glass which will hold the standard wedge and test film is clean.
3. Place a 21-step tablet, emulsion side up, on the supporting glass.
4. Turn the power to the sensitometer "on".
5. If the exposure time of the flashtube can be varied, depress the necessary exposure time switch.
6. Raise the cover platen.
7. Extinguish all darkroom lights.
8. Insert a suitable length of test film emulsion down on top of the standard step wedge.
9. Lower the platen until the flashtube has been triggered. (Usually a click will be noticeable and serves as an indicator that an exposure has been made.)
10. Raise the platen, remove the film strip, and process as prescribed. (The particular processing will depend on the application.)

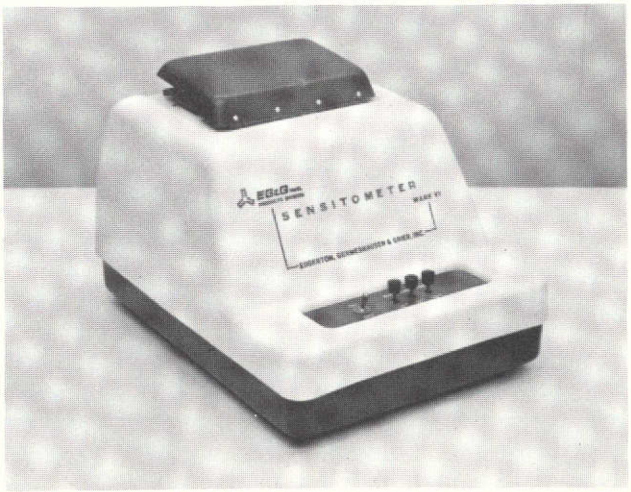


Figure 69. E.G.&G. laboratory sensitometer.

When these steps have been performed, the user will have a test film from which a characteristic curve can be generated. Two types of characteristic curves will be described in this chapter. They are the relative log E curve and the log E curve. Consideration will then be given to specific applications and interpretation of the data contained in these curves.

6.1 Density vs. Density (Relative Log E) Curves

After processing, the sensitometrically exposed step wedge is read on a densitometer and the data is plotted. The simplest form of characteristic curve for any emulsion consists of plotting the densities recorded on the tested film strip against the densities of the original step wedge. The procedure for plotting such a curve is as follows:

- The densities of the original step tablet used to expose the film, are read and recorded.
- The densities obtained on the test film strip are read and recorded.
- A data sheet, such as that shown in Figure 65 is used to plot the measured densities. The y axis represents the measured density values of the test strip and the x axis represents the steps (or densities) of the original tablet. Since no attempt is made to determine the photographic exposure of each step, the measurements are only *relative*.
- For each step of the original tablet, plot the corresponding test density along y. Continue until all points are plotted.
- These plotted points are connected by a best fit curve through them and the result is known as a characteristic curve, an H & D curve, or a relative log E curve.

Figure 70 shows a typical plot of relative log E. Since all characteristic curves look somewhat similar, every graph should contain all the densitometric measurements, as well as the pertinent information regarding development time, chemistry, film type, etc. Most sensitometer and densitometer manufacturers will supply data sheets similar to that shown in Figure 70 if a specific format is required. In any event, some standardized form should be used for the efficient tabulation and preservation of sensitometric data.

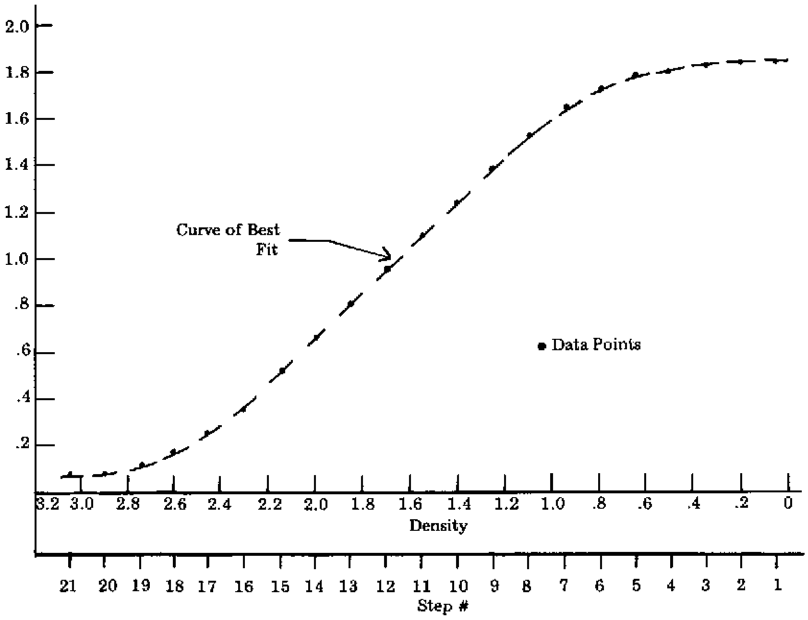


Figure 70. Plot of density vs. density or relative log E.

6.2 D log E Curves

To construct a D log E curve (not relative log E), it is necessary to determine the logarithms of the exposures which created the densities on the test film. Since exposure is equal to illumination multiplied by time, we need only consult the sensitometer manufacturer's data for the lamp output (I) in meter candles and the pulse time (t) in seconds. These values are multiplied together to obtain the maximum exposure; the logarithm of this maximum exposure (log E_m) may be immediately determined. It will be noted that the output of the sensitometer is modified by the densities of the 21-step tablet. To determine the value of log exposure (log E) for *each* of these steps, it is necessary to subtract the density of each step from the maximum exposure. For example,

$$\text{Log E}_{\text{(Step E)}} = \text{Log E}_{\text{m}} - \text{Density}_{\text{(Step 8)}}$$

The log E values thus obtained for each step of the standard step wedge will be invariant provided that the sensitometer light output and exposure time do not change. (Generally, sensitometers are constructed so that the light output is constant over very large periods of time. Light meters do not exist verifying sensitometer stability, however.)

Plotting D log E curves is relatively simple; the y axis represents the density and is marked off in increments of 0.2 density. The x axis is marked off in units of log exposure with the lightest step (usually #1) to the extreme right and the 21st step on the extreme left side of the axis. The density of each step is read from the test film and recorded. The calculated log E's of each of the 21 steps are marked off along the x axis and the recorded densities of the test film are plotted in their proper positions above them. A typical D log E curve is shown in Figure 71 with the actual exposure values, as well as the log exposure values shown along the x axis. The pertinent sensitometric and densitometric information and measurements should also appear on the graph as they are in Figure 66.

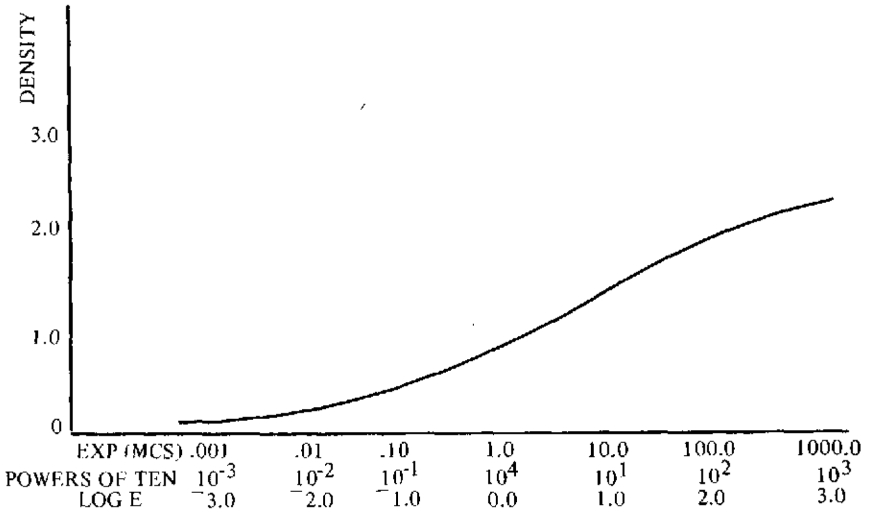


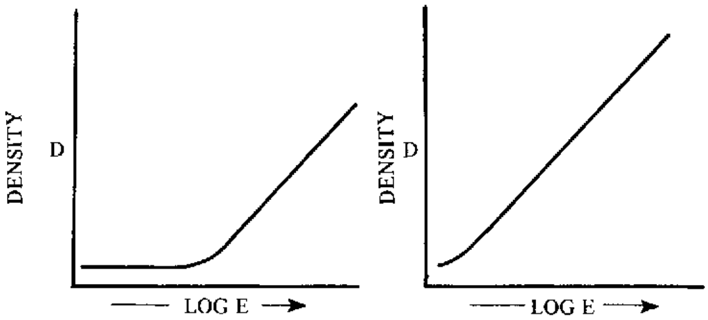
Figure 71. Typical D log E curve showing the exposure values, as well as the log E values along the x axis.

The D log E curve is a graphical representation of the exposure-development relationship. Increasing the exposure will cause the curve to be shifted towards the right, as shown in Figure 72a, while decreasing exposure will move the curve to the left (see Figure 72b). Hence, when setting up the x axis values, consideration must be given to the exposure used in order to accommodate the range of log E's. Figure 66 shows a typical log E range.

All D log E curves possess the same general shape which may be divided into four regions shown in Figure 73.

- The area of lowest density, called the toe, in which the ratio of density to log E increases as value of E increases. The lowest density will never be zero; it will have a finite value representing the density of both the film base and its fog level.
- The central region, called the straight line, in which the ratio of density to log E is a constant as E increases.
- The upper region, called the shoulder, in which the ratio of density to log E decreases with exposure.
- If the exposure is increased still further, the process known as reversal takes place. That is, the density of an area will decrease with further exposure.

Almost all images will have densities which exist on the toe and straight line portions of the curves; although some images may occasionally fall on the shoulder, generally none will exist in the region of reversal unless the film is specifically processed for that condition.



(a) (b)

Figure 72. Lateral shift in the D log E curve caused by differences in exposure.

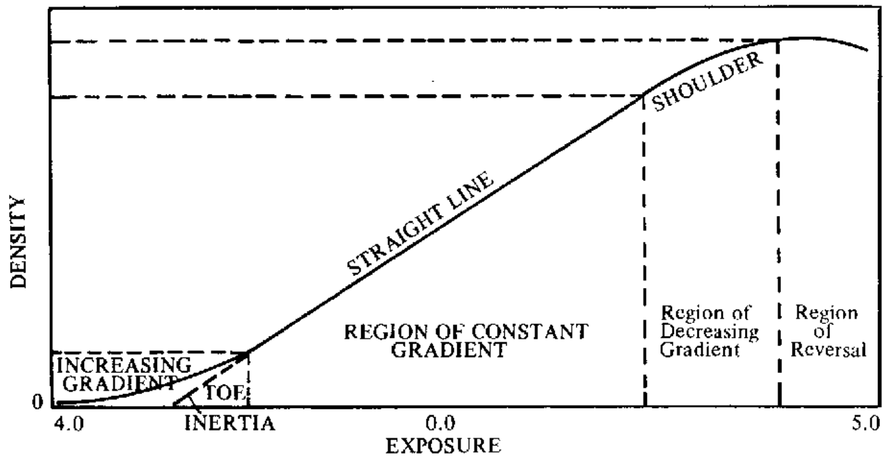


Figure 73. The components of D log E curve.

6.3 Use of Characteristic Curves

6.3.1 Film Speed

The speed of an emulsion can be readily determined from a characteristic curve exposed and processed in a *predefined* manner. Many different methods of computing film speed have been devised over the years and they may be classified according to that portion of the characteristic curve which is thought to be important for a particular application. There are three basic speed groups:

- Threshold speeds — based upon the assumption that the minimum density (D min) will not fall below a predefined value, usually on the toe or the straight line. Pictorial negative emulsions, both color and black-and-white, are given speed values of this type. For example, H & D speed, ASA, DIN, and Aerial Exposure Index.
- Midtone speeds — based upon the assumption that satisfactory images are produced when they fall at about the center of the H & D curve. Reversal films specify speeds of this type.
- High density speeds — based upon the assumption that the images are all of high luminance, such as industrial x-ray, microfilm subjects, etc.

It should be noted that speed values quoted by manufacturers usually include a tolerance of about ⅓ stop. That is, a film with an ASA rating of 125 could actually possess any speed between about 105 and 145. Poor storage or overaged film will naturally extend these tolerances. Hence, if an accurate measure of speed is required, appropriate experimental sensitometric tests must be made.

Threshold Speeds

H & D Speed — this speed value was based upon the assumption that the objects of interest must fall on the straight line of the curve and the lowest possible exposure must be at the beginning of the straight line. Often the point defining these conditions is difficult to determine since many films do not possess true straight line. The solution to this dilemma is to extend the straight line of the H & D curve (or the average straight line) so that it intersects the x axis at a point called the inertia (i) (see Figure 74); the speed is then defined as:

$$\text{Speed} = \frac{34}{(i)}$$

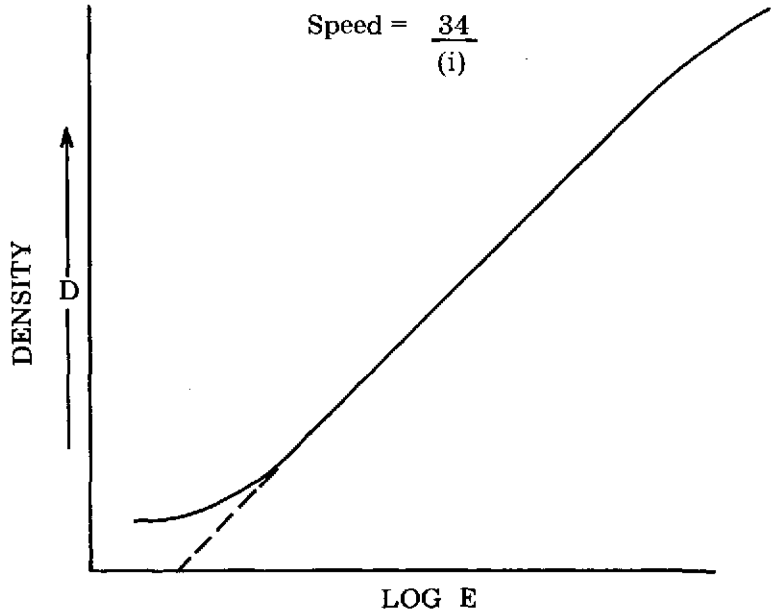


Figure 74. H and D (inertia) speed.

Generally, H & D speeds are no longer used and have been replaced by either ASA or DIN for pictorial photography. Multispectral photography requires use of the straight line so that the ASA film speed specification is valid for this application.

ASA Speed — to determine the ASA speed rating of an emulsion, a number of sensitometric wedges are exposed onto the test film, each wedge being processed to a different development time. The curve selected to determine the ASA speed must have a specified shape (that is, contrast). The correct shape of the curve is determined in the following way and reference is made to Figure 75.

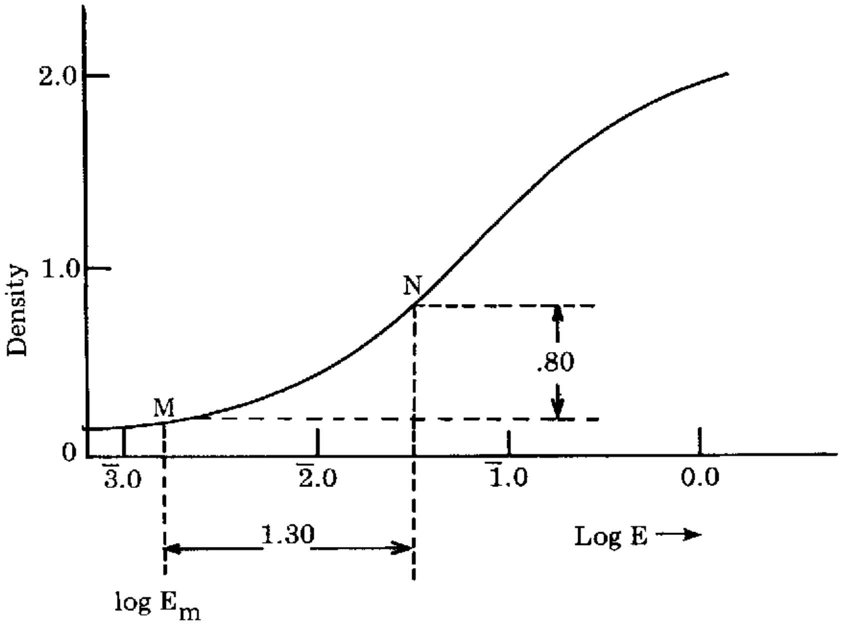


Figure 75. Method for determining ASA speed for black-and-white films.

- Select the point (M) which is .10 above base, plus fog density on the H & D curve.
- Measure to the right of point M, 1.30 log E units and call the second point N.
- The density difference between points M and N must be .80.
- Increase or decrease the gamma (development time) until this density difference between M and N is obtained.
- The arithmetic ASA speed, S_x, is given by:

$$S_x = .8/E_m$$

where E_m, is the log E value of the point M which is read from the log E axis.

DIN Speed — this film speed is rarely used since, in 1954, its specification was changed to coincide with the ASA specifications. The DIN speed was based upon the exposure necessary to produce a density of .10 above base fog.

$$\text{DIN speed} = \log\,(.49/E_{.10})$$

where $E_{.10}$, is the exposure corresponding to the density level of .10.

Aerial Exposure Index — this speed value is generally used by the U.S. military and is also a gradient method. AEI is determined in the following way:

- Plot the H & D curve of the emulsion.
- Determine the gamma of the film (see following section).
- Take 60% of that gamma.
- Find that point on the curve where the slope is 60% of y and measure the log E at that point.
- AEI speed = .5/E

This method of specifying speed is not often used; it can be misleading in that the index sometimes decreases with increasing contrast which is generally not the case with ASA.

ASA Color Speed — since color negative films consist of three layers sensitive to red, green, and blue light, the method of calculating ASA speed for color films requires an averaging of the speed point, E_m, of each layer. To determine the average value of E_m, the following procedure is used:

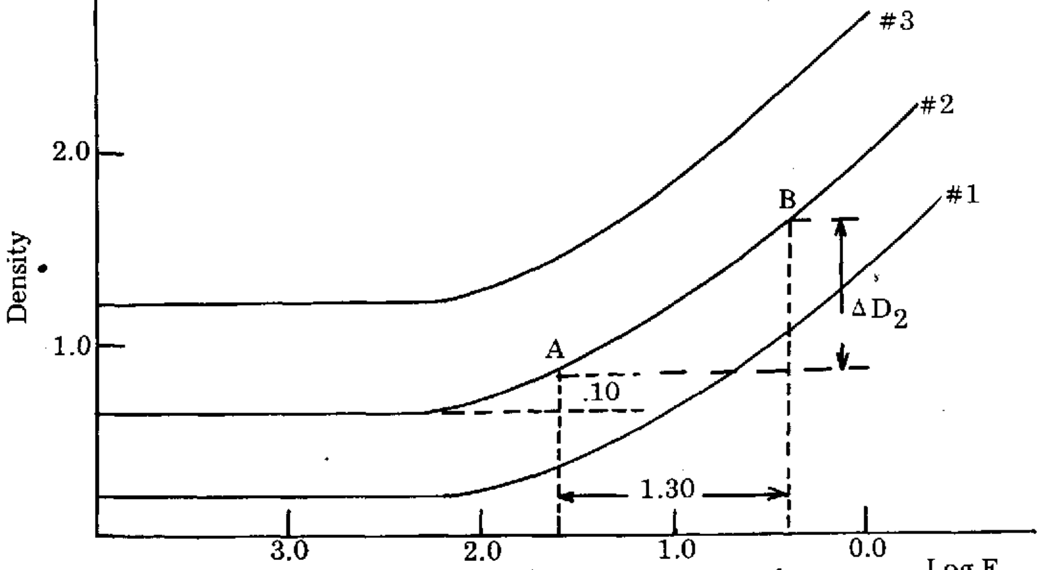


Figure 76. First steps for computing ASA color negative speed.

- Plot the H & D curve for each layer on the same graph as shown in Figure 76.
- Locate the point A which is 0.10 density above fog for the center curve #2.
- Locate a second point B which is 1.30 log E units to the right of A on curve #2.
- Determine the density difference (ΔD_2) between points B and A. Take 20 percent of ΔD_2 and call that value m.
- Determine the fog level for curves #1, #2, and #3.
- Measure m density units up on each curve and mark these points R,G, and B respectively. Refer to Figure 77.
- Measure the corresponding values of log E for R, and B called E_R, E_G, and E_B.
- Compute the average log E_m as:

$$\text{Log } E_m = \frac{\log E_R + \log E_G + \log E_B}{3}$$

- ASA color speed equals 1/Em.

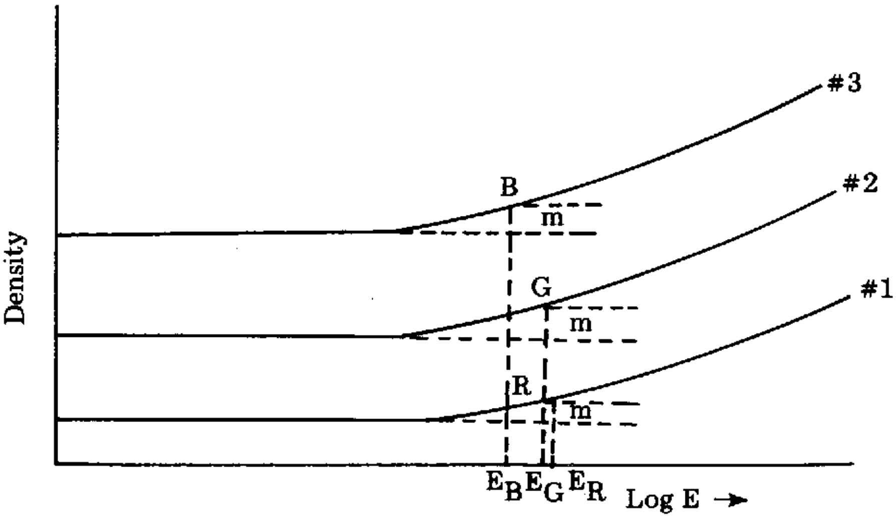


Figure 77. Final steps in determining ASA color negative speed.

Midtone Speeds — these speeds are based upon the assumption that reproduction of the midtones is more important than the shadow detail. Film speed values for astronomical use are based upon a density of .6 above fog and are computed as 1/E. Medical x-ray films also have speeds defined as 1/E, although they are based on a density of 1.0 above base fog.

ASA Reversal Speed — whereas the ASA value of a color negative emulsion was based upon threshold speed, the ASA value of a reversal film is based upon midtone speeds. Unlike color negative materials, the ASA speed of a reversal film is found by plotting a single H & D curve; that is, by measuring the total diffuse density through the layers simultaneously. The resultant curve will look similar to Figure 78 in which the shape of the curve is reversed from that of the color negative emulsion since the reversal film is a positive. That is, the highlights have less density than the shadows. Referring now to Figure 78, the point H is determined at a density value of 0.20 above base fog and represents the general highlights of the scene. A line tangent to the H & D curve is drawn from H. One, and only one, such point should exist and is labeled as S for shadowed areas. Generally the tangent point S occurs at densities less than 2.0; when S occurs at densities greater than that value, it is placed at the level of 2.0. That is, the density associated with S is never greater than 2.0. The corresponding log E values are measured as E_H and E_S respectively. The vlaue of E_m is then computed by:

$$E_m = \left[E_H \cdot E_S\right]^{1/2}$$

and the ASA speed value is:

$$\text{ASA speed} = 8/E_m$$

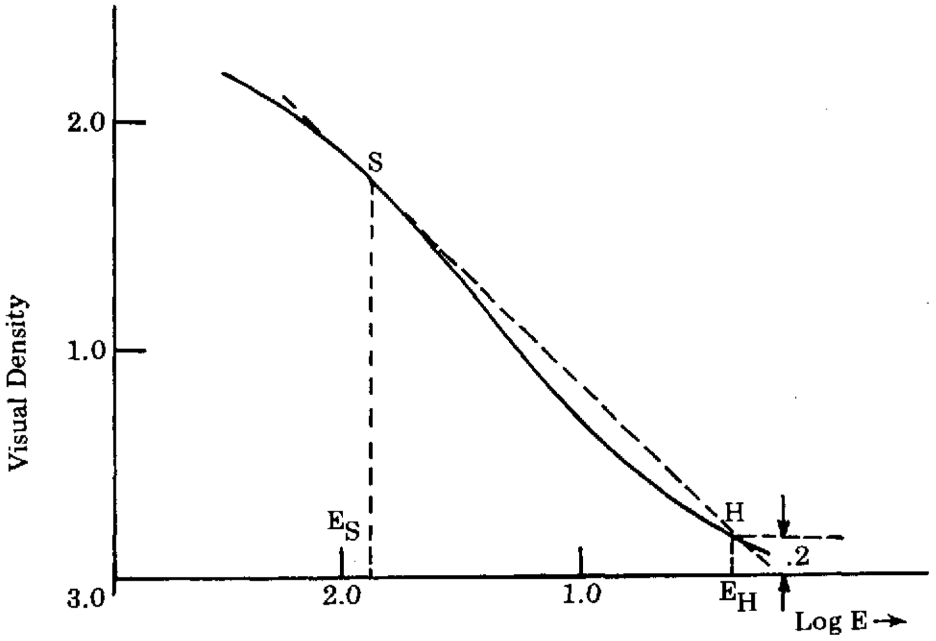


Figure 78. Method of determining speed of a color reversal film.

High Density Speeds — the use of high density speeds assumes that the accurate reproduction of high luminance areas or white is essential.

Microfilms specify the speed of the emulsion, measured from a density of 1.2 above base fog, as being:

Speed = 45/E

Industrial x-ray film speeds require a net density of 1.5 above base fog and are defined as:

Speed = 1/E

Positive transparency films, which are used for pictorial subjects, require that the exposure E be determined at that point where the net density is 1.20. The speed formula is:

Speed = 1000/E

Differences in the slopes or gammas of the characteristic curves necessitate that the significant portion of the curve be clearly defined for speed specification. Figure 79 illustrates this point. Films A and B have the same gammas, although their toes are considerably different. A speed specified along the straight line portion of the curves would yield the same value for both films A and B. If, however, the speed point was defined at the toe of the curve, film A would be faster than film B since it requires less exposure to reach the desired density level (d). Speed also depends upon exactly what density level is measured, as shown in Figure 80. If the speed is measured at the toe, then film A is faster than film B; if the speed is defined along the straight line, than we would conclude that the films possessed about the same speed value. Measurement of speed at high density levels would show that film B was faster than A.

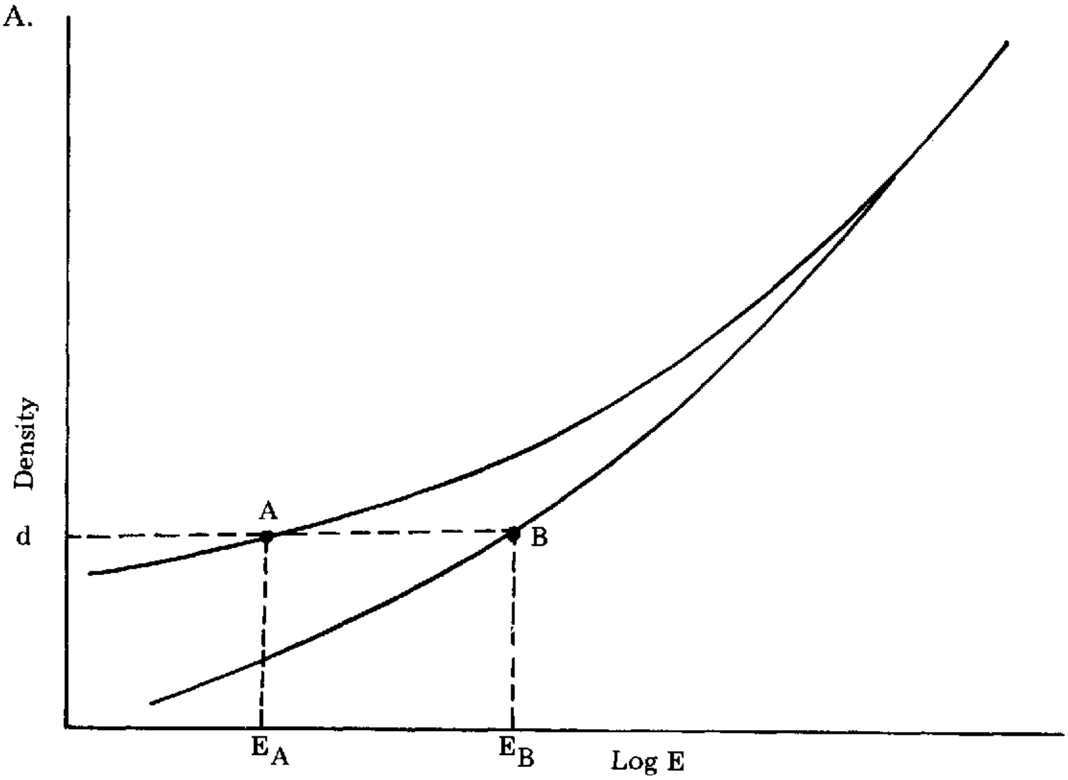


Figure 79. Film speed depends on the gamma of the film.

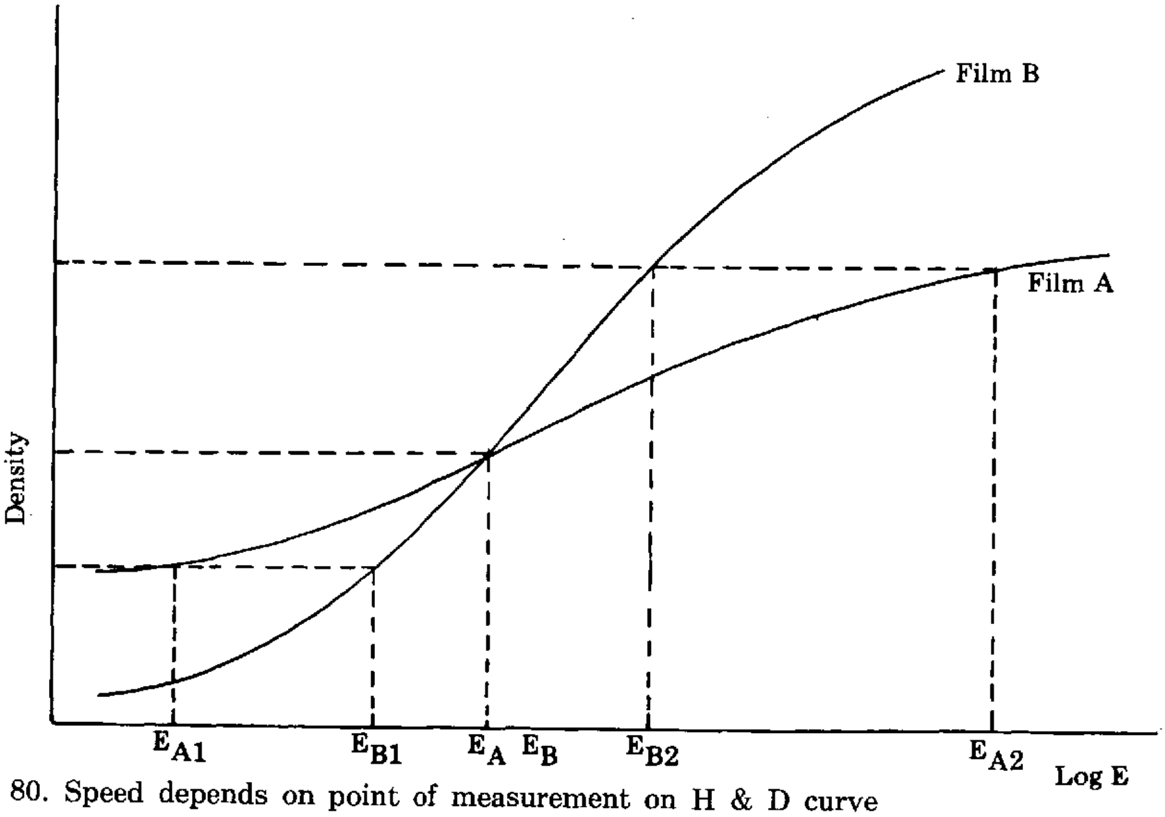
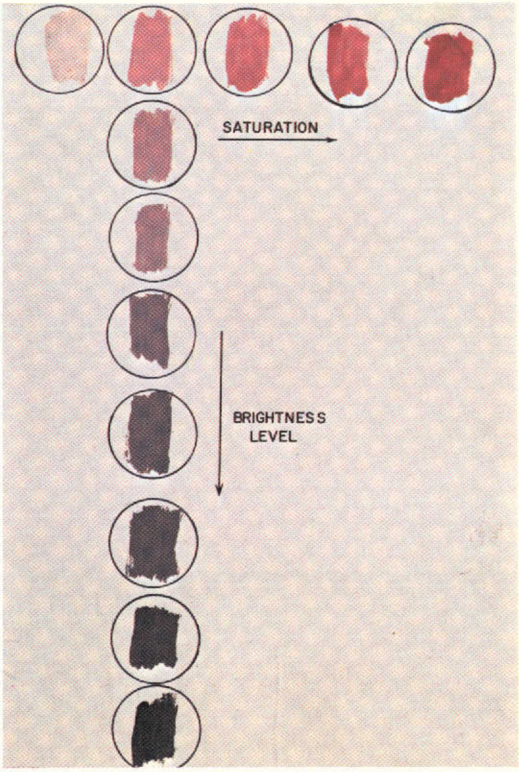


Figure 80. Speed depends on point of measurement on H & D curve

PLATE I — Color variables of saturation and brightness, for a red hue — dominant wavelength 670 nanometers. Saturation consists of the amount of white contained in a color. At zero percent saturation, the color tends to white or gray, while at 100 percent saturation the color is identical with the pure hue. Saturation is that characteristic of a color which makes pale yellow different from canary yellow. The brightness level of a color is shown along the vertical column and represents a measure of the amount of black contained in the color. As the brightness level decreases to zero, all hues approach pure black. For each degree of saturation there exists a multitude of brightness levels and conversely every brightness level also contains varying levels of saturation. In this figure only one level of saturation and one level of brightness is shown.



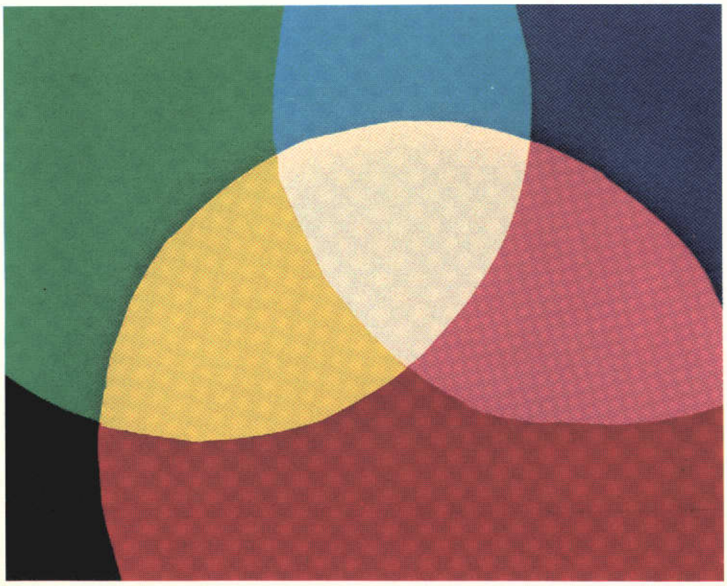


PLATE II — Additive reproduction of color. Projecting three primary hues so that each one overlaps the other shows that the combination of red and green produces yellow. The additive combination of blue and red produces magenta while green and blue yields cyan. The addition of all three primary lights results in white. By decreasing the relative brightness of each of the three primaries, a complete gamut of both primary and secondary colors is produced. Decreasing the brightness of each lamp by the same amount produces resultant colors which are darker in value: i.e., royal blue becomes navy blue.

6-10-a

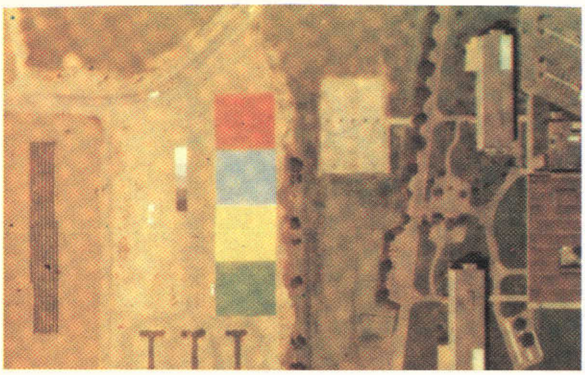


PLATE IIIa

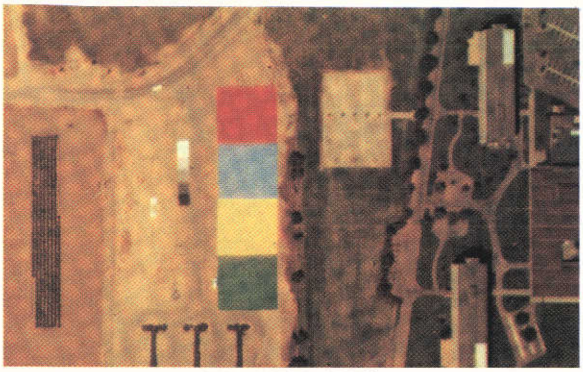


PLATE IIIb

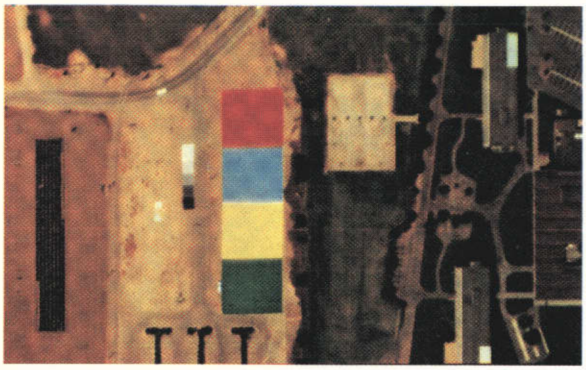


PLATE IIIc

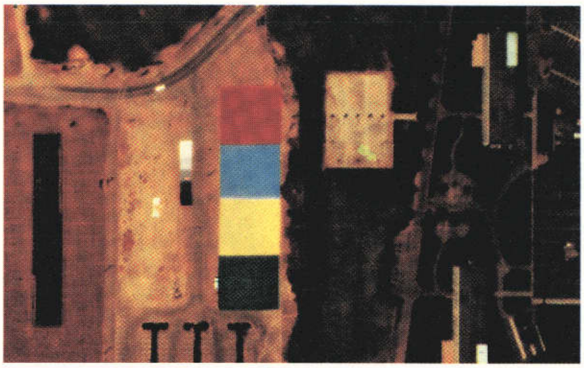


PLATE IIId

PLATE III — Four color panels, as well as a black-and-white gray scale, have been placed in the scene and the effect of increasing the gamma of the multispectral positive records is shown. The gamma ranges from .6 in the upper left hand figure to 2.3 in the lower right hand photograph. The effect of such an increase in contrast can be seen as a distinct increase in the saturation level of the colors in the final multispectral rendition. Each multispectral band of each of the photographs above have been processed to exactly the same gamma. A differential gamma between the records would produce a gray scale which was not neutral.

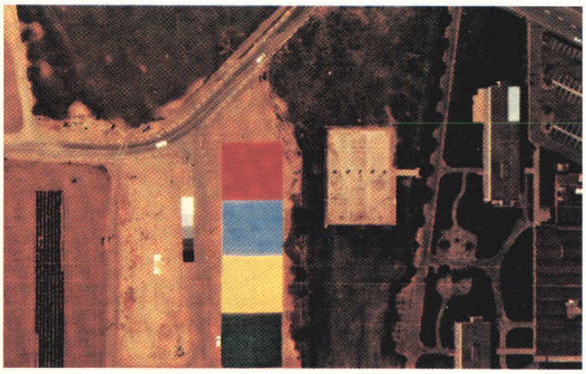


PLATE IVa

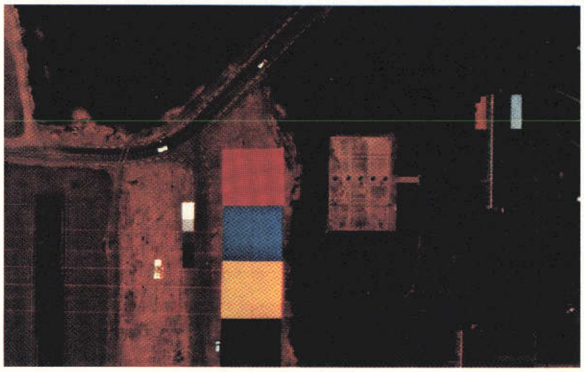


PLATE IVb

PLATE IV — An increase in the camera exposure results in an increased density on the multispectral records or a loss in color for the dark objects in the scene. Notice the green panel in figure IVb has a brightness level very close to black. Both multispectral renditions have been processed to exactly the same gamma, i.e., 2.0.

6-10-6

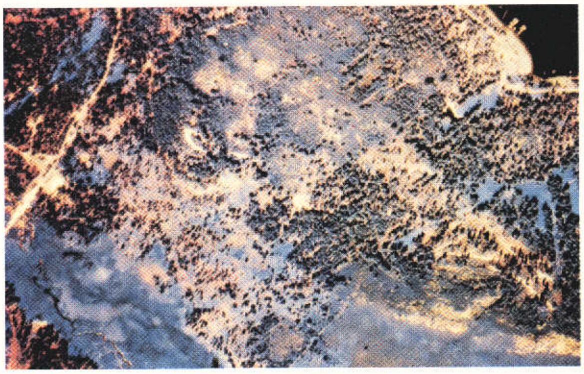


PLATE Va

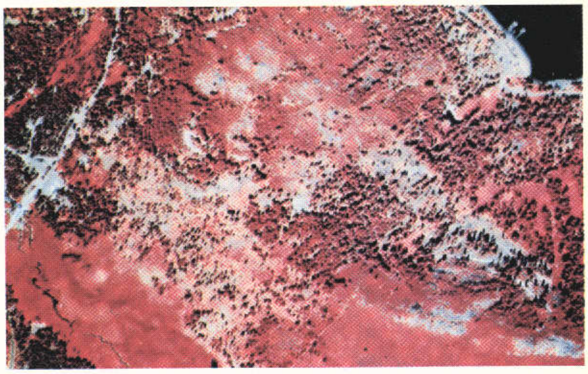


PLATE Vb

PLATE V — Multispectral additive color photography permits the interpreter to alter the three variables of color — hue, brightness and saturation. Plates Va, Vb, and Vc are multispectral false color renditions of a forested area around the Bucks Lake, California while Vd is a multispectral simulation of Ektachrome film. The sparsity of vegetation at the bottom of the photos is apparent in Va and Vc while the simulated Ektachrome and Ektachrome Infrared renditions falsely indicate that the area is lush. The body of water in the upper right corner is projected as black since water absorbs both red and infrared radiation to a great extent. Complete interpretation of multispectral imagery is dependent upon examination of the scene in a multitude of additive color renditions. This frame of imagery was exposed using broadband filters in the camera, namely, red, green, blue and near infrared. The first three of the set also incorporated an infrared blocking filter since they transmit readily in the 700-950 nanometer region of the spectrum. Plate Va was projected using blue, red, and green filters for the infrared, red and green taking filter photos. Plates Vb and Vc projected the IR, red and green taking filter photos as red, green, blue and green, red, blue respectively. The simulated true color rendition of Plate Vd projected the red, green and blue taking filter photos as red, green and blue.

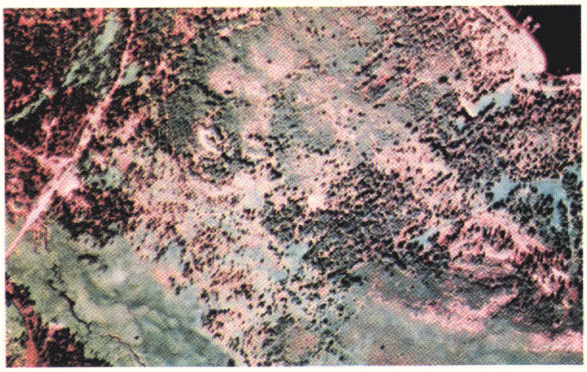


PLATE Vc

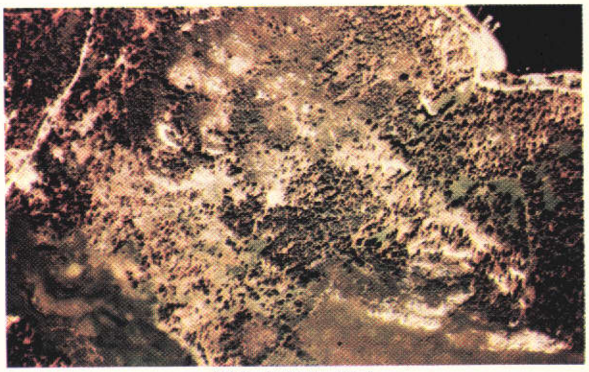


PLATE Vd

PLATE VIa — False color multispectral rendition of marsh land area in Louisiana. Two different species of marsh grass predominate. Upland vegetation is a cyan-green while grass along the water edge is purple.

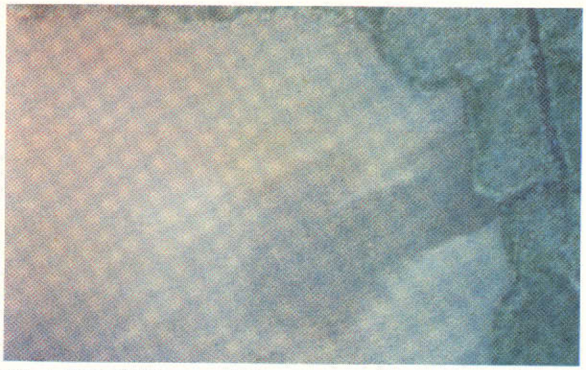


PLATE VIb — The use of narrow band filters in the multispectral camera permits detection of subtle phenomenon such as this plankton bloom in the water area between Sawdust Bayou and South Pass in the Mississippi Delta.

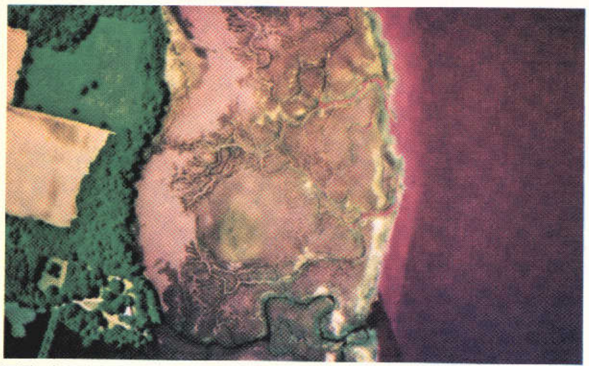


PLATE VIc — Multispectral narrow band, false color rendition of a South Carolina marsh. The stream in the lower portion of the photo shows black indicating pollution. The stream at the top is red, the water mass being clean.

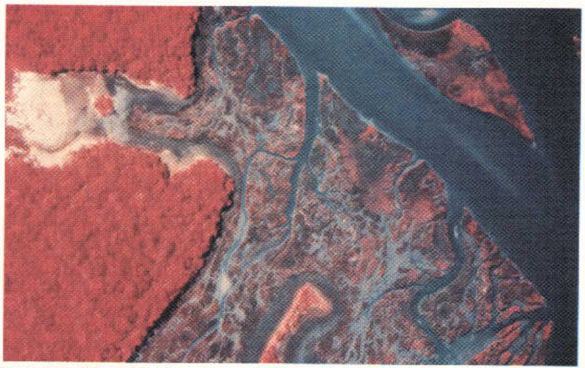


PLATE VId — Speciation of marshland vegetation is facilitated using narrow band camera filters. Disticulus sp, Typha sp, S. Alternaflora, Salicornia bigelovii and Juncus roemerianus can be distinguished by their photo colors.

PLATE VIe — A coastal area in Massachusetts has been photographed to determine the water penetration ability of multispectral imagery. Beach areas are pink while the open water is blue. Shades of magenta represent various depths.

PLATE VIf — The presence of a salt-fresh water interface in an estuary of Massachusetts is visible as a light yellow against an orange background. The center plume was only apparent on one of the multispectral records.

6-10-d

PLATE VIIa — Conventional Multispectral photograph of the Gunnison Hills area, Arizona. Varying terrain brightness causes difficulty classifying the soil-vegetation units on left and right of photo.

PLATE VIIb — An isoluminous rendition of the same photograph shown in Plate VIIa. The removal of all brightness differences creates an image, the color variations of which represent changes in the soil spectral distributions.

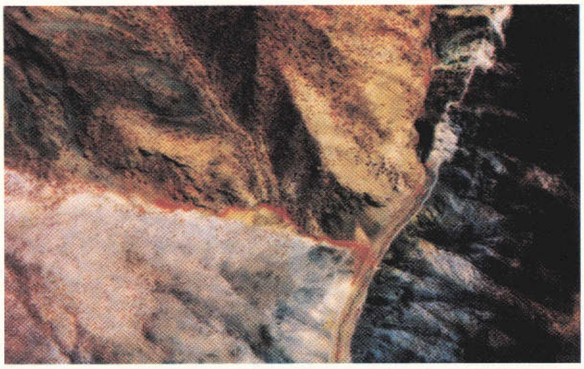


PLATE VIIc — Simulated Color Infrared photograph of White Mt. area, California. Differences between sedimentary and volcanic rocks as well as fault contacts are clearly visible in this presentation.

PLATE VIId — Conventional Color Infrared photograph of-the same area as Plate VIIc. Fixed exposure ratio between the dye layers prevents detection of rock types and fault contacts.

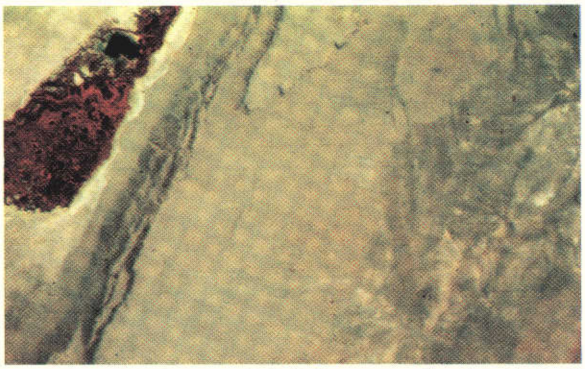


PLATE VIIe — Multispectral simulated Color Infrared photo of Owens Desert California. Flood plain deposits are red; non welded tuff is yellow-green while partially welded tuff tends to grey-green.

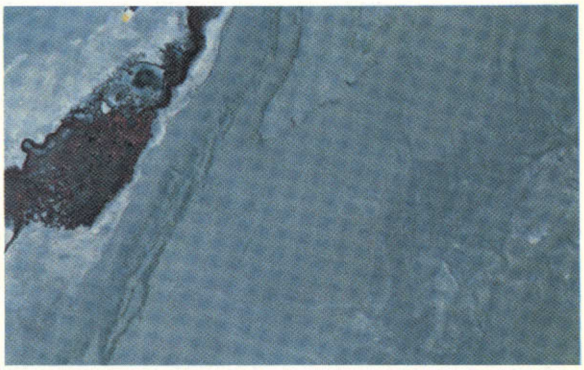


PLATE VIIf — Conventional Color Infrared photograph of same area as Plate VIIe. Overall blue cast to the image is caused by a larger green exposure ratio in the dye layers.

6-10-e

PLATE VIIIa — An additive color rendition of Apollo IX multispectral photograph #3799. The color difference between vegetation, soil and water was enhanced so that no color overlap exists between these land use categories.

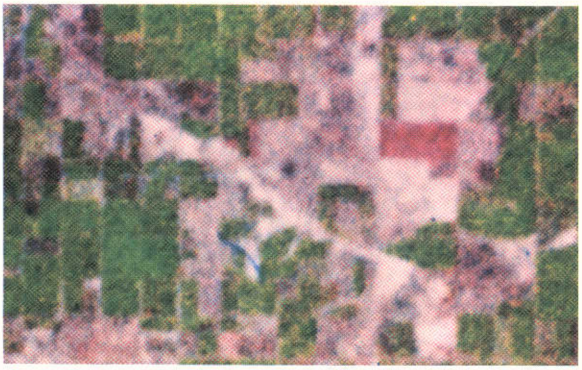


PLATE VIIIb — A twenty times enlargement of a portion of Plate VIIIa. An analysis of the multispectral color showed that barley, alfalfa and sugar beets could be differentiated from other crops grown in Imperial Valley.

PLATE VIIIc — A conventional multispectral photograph of an avacado grove which is partially infested with root rot disease. A color difference between the healthy and diseased trees does not exist here.

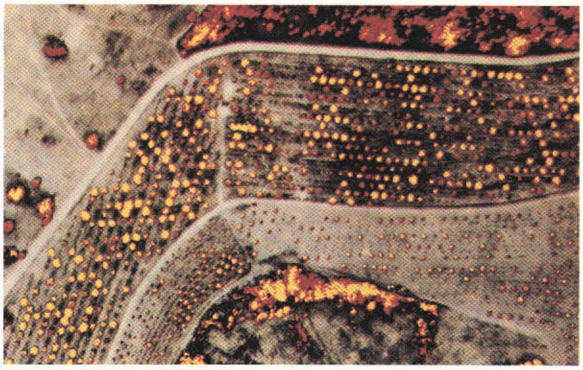


PLATE VIIId — A multispectral isoluminous rendition of Plate VIIIc in which the healthy trees are a vivid yellow color while the diseased trees are a brilliant red. Disease detection is possible here.

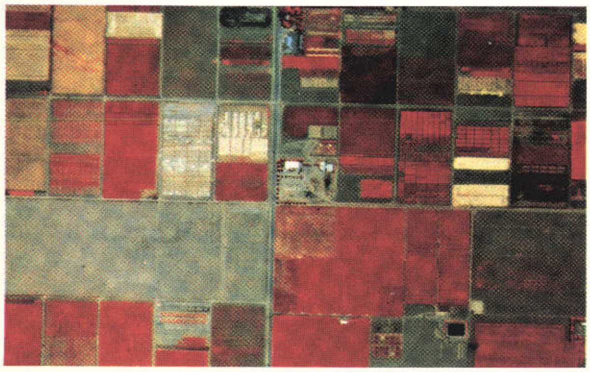


PLATE VIIIe — Multispectral simulated Color Infrared photograph exposed over Davis California. Alfalfa, barley, corn and tomatoes can be differentiated solely by their chromatic characteristics.

6-10-f

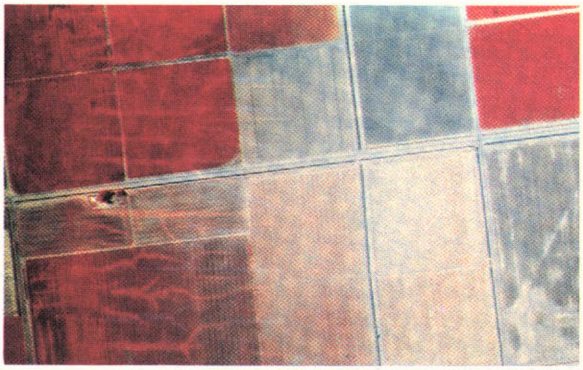


PLATE VIIIf — Multispectral simulated Color Infrared photograph exposed over Imperial Valley, California. Bare soil, cotton and sorgum as well as alfalfa on rye grass are identified due to their unique color signatures.

PLATE IXa

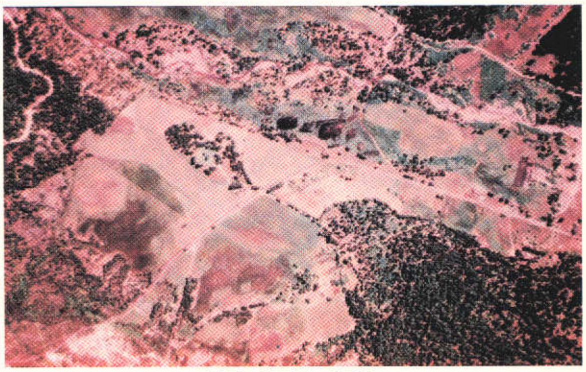


PLATE IXb

PLATE IX — Forestry Applications: Plate IXa is a false color multispectral rendition of a forest stand in Yosemite Valley. The larger oak and cottonwood trees are presented as a saturated pea-green hue while the pine and cedar conifers are a brownish purple. Plate IXb taken over the Meadow Valley — Bucks Lake region of California shows the medium to high density conifers as deep green. The low density conifers are pink due primarily to the superimposition of the soil which is light pink. Wet and dry meadow sites are also a pinkish color. Plate IXc taken in the same Bucks Lake area presents the medium to high density conifers as a deep blue while the low density conifers are yellow-orange. The wet and dry meadow sites to the left of the lake are light blue. The lake itself is projected as black due to the infrared absorbtion properties of the water mass. Plate IXd was also exposed over the Bucks Lake region and the blue to cyan portions of the photograph indicate bare soil and rock. The medium to high density conifers are a distinct magenta color while the brush and dry site hardwood range from deep red to light magenta. There exists little difference between the wet and dry meadow sites and the brush-dry site hardwoods, both having the same magenta color in general. Plates IXa and IXb were exposed using narrow band camera filtration while the Plates IXc and IXd were exposed through broadband blue, green, red, and infrared filters.

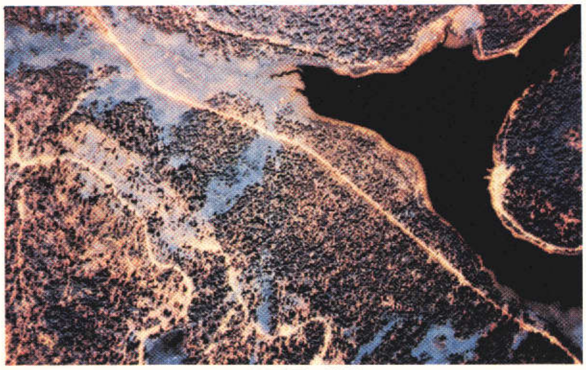


PLATE IXc

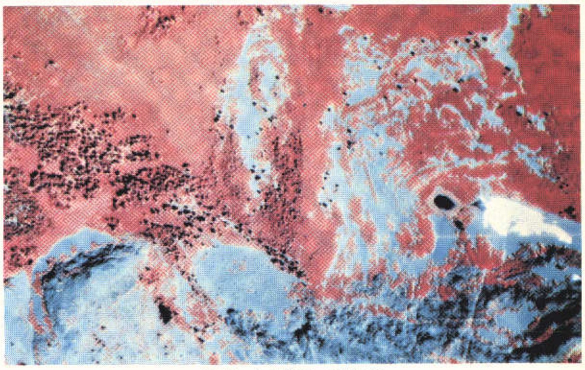


PLATE IXd

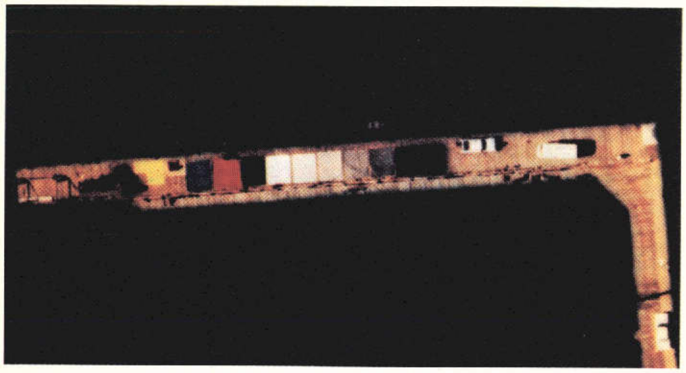


PLATE Xa — This photograph shows a dock off Montauk Point, New York, in which two sets of targets have been embedded into the scene. A color and gray scale have been placed on the top of the dock and the second set has been submerged alongside it. The processing and exposure of this figure was such that reproduction of the highlighted areas is maximized.

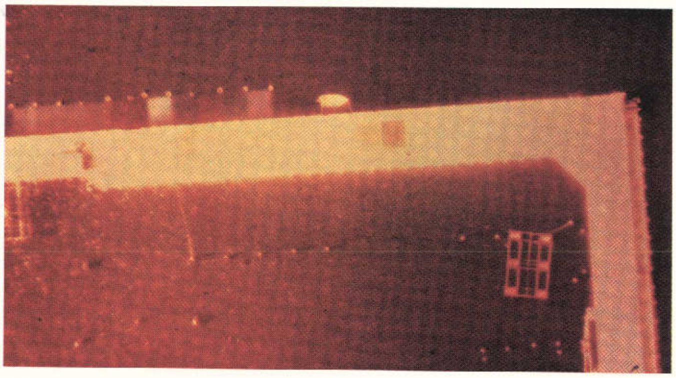


PLATE Xb — Optimal exposure and processing for shadowed areas reproduces the submerged panel array fairly accurately. However, the target array on the dock (in the highlights) is not reproduced at all. Hence, if one is concerned with interpreting low-brightness areas, the exposure must be selected for that portion of the scene and with no regard for the highlighted areas.

PLATE Xc — This presentation consists of a special processing-masking procedure called isoluminous photography. All brightness levels have been reduced to a common value as can be seen from a comparison of the individual gray scale, i.e., the white panel is approximately the same color as the black panel while the color targets maintain vivid hues. It is this technique which permits information contained in both the shadow and highlighted areas to be reproduced simultaneously on the same photograph. Notice also that the yellow surface panel which has a shadow falling across it in Plate X-a is now reproduced without any loss of chromaticity in that corner.

6.3.2 Gamma

The gamma or processing characteristics of a film can be determined from an examination of the H & D curve. This quantity is defined as the slope of the straight line portion of the characteristic curve (see Figure 81) and is determined by the following equation:

$$\gamma = \frac{D_2 - D_1}{\log E_2 - \log E_1}$$

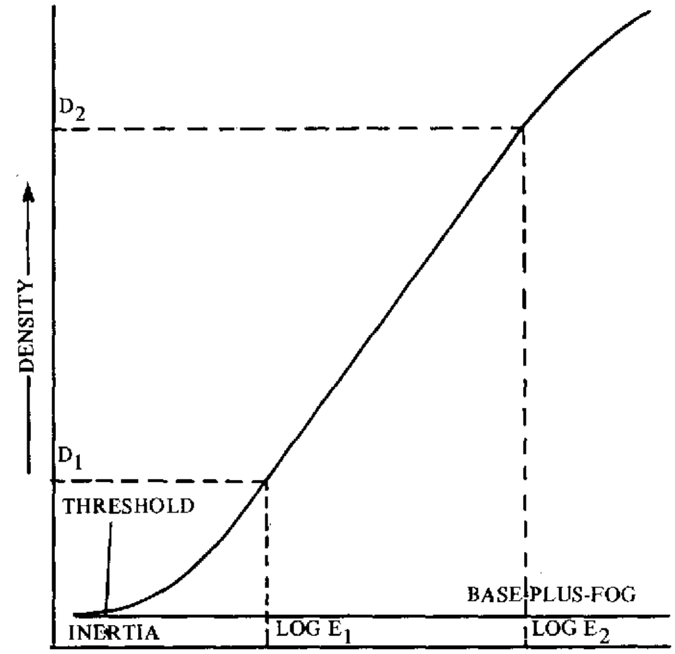


Figure 81. Gamma is defined as ratio of change in density to change in log E.

The gamma is a means of expressing the degree of emulsion development or the effect of development upon the characteristic curve.

If it becomes inconvenient to determine the values of D_1, D_2, $\log E_1$ and $\log E_2$, from the curve, the gamma may also be determined graphically. The straight line of the H & D curve is extended so that it intersects the x axis. By moving to the right of that point, a distance equal to 1.0 log E units, and reading the corresponding density of this second point, then that density will equal the gamma. The only condition to this method is that the density of the second point must fall on the straight line. The use of a gamma meter is also a rapid means of determining the gamma, especially if many samples are involved. Figure 82 shows such a meter and Figure 83 demonstrates its use.

Since the degree of development is indicated by the shape of the H & D curve and the slope of the straight line portion, any increases in development time will cause the straight line to be steepened. Larger density differences will result for the same exposure values as shown in Figure 84. The effect of increased development upon gamma is shown in Figure 85 and one shold note that there exists a processing time after which further development will not increase the gamma of the image.

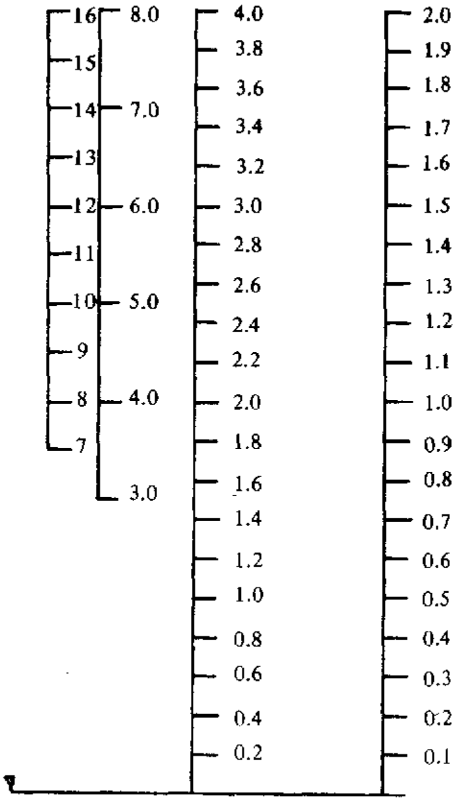


Figure 82. Gamma Meter

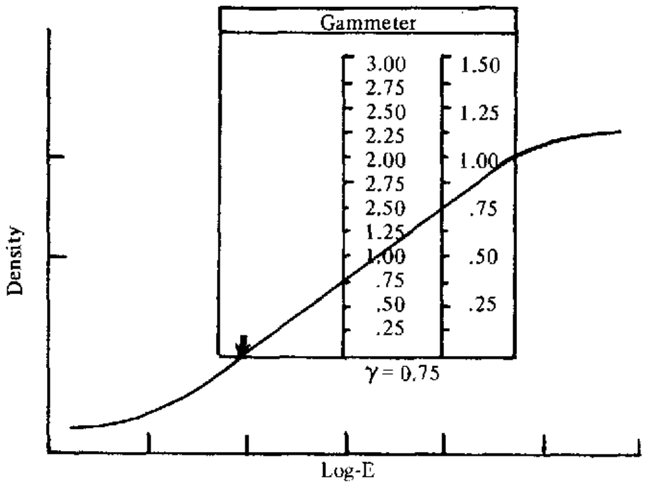


Figure 83. Use of Gamma Meter.

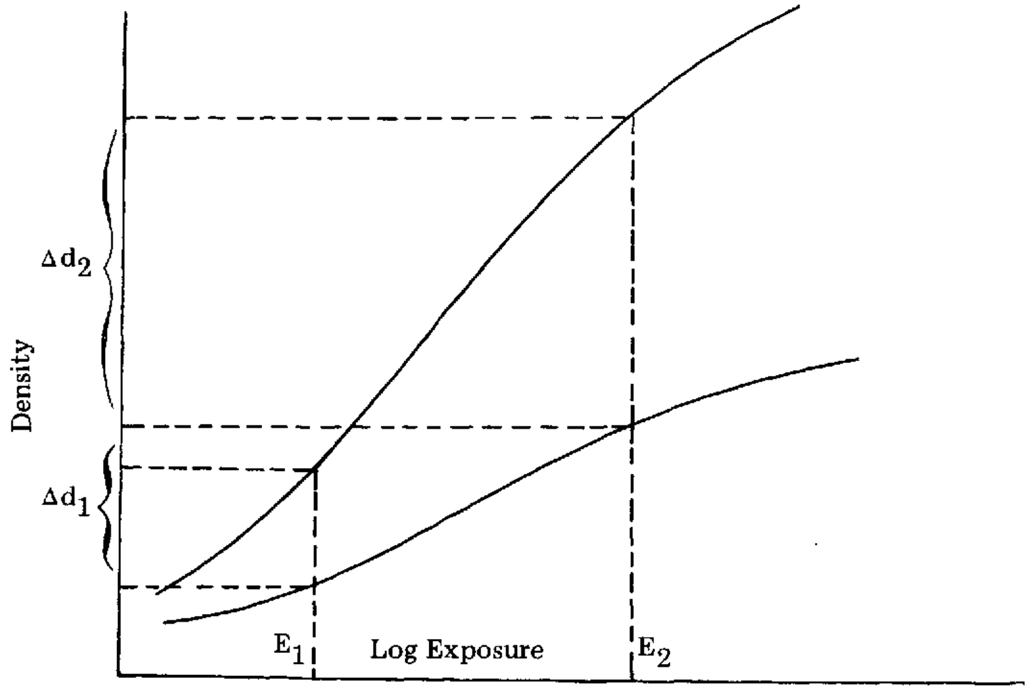


Figure 84. Higher gamma creates larger density differences between images.

Such a family of H & D curves, varying with development time, is generated by exposing a number of sensitometric wedges and processing each for a different length of time. All other conditions, such as developer strength, agitation, etc., must be constant for all wedges. The densities of each step of the wedge are read on a densitometer and plotted on the single graph of Figure 85. Several things can be seen from an examination of this figure, such as:

- The toe regions for all curves are about the same, regardless of the development time.
- The length of the straight line portion is greatest at low gamma.
- The slope of the curves increase with increasing development time.

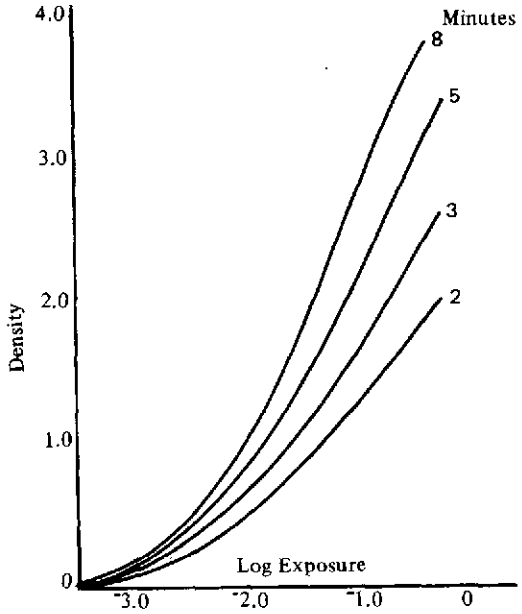


Figure 85. A set of characteristic curves representing different development times (aerial film, D-19 developer at 68°F).

It is evident, therefore, that the tones of an image will change with processing, depending upon their *exposure* or where on the H & D curves they lie. For example,

- An image which is underexposed (on the toe) can never result in significant densities, regardless of how long the film is processed.
- An image which falls on the straight line or shoulder can be made more or less dense depending upon the development time.

Gamma has often been equated with the concept of contrast. This is, in fact, incorrect since gamma is *only* a measure of the development conditions, including agitation time, chemical strength, and temperature. The total contrast of a negative is actually the density difference between the deepest shadows and the brightest highlights contained in the film. As such, it is dependent upon many factors, including exposure, spectral distribution of the illuminant, brightness ratio between shadows and highlights, and processing conditions or gamma. Hence, gamma is only one factor which affects the total contrast of a negative. By way of illustration, consider exposing an emulsion to a scene which does not have a very great ratio between the highlight and shadows. Regardless of how long the film is developed (resulting in a high gamma), the image will not be contrasty. Similarly, exposing a film to a scene containing a large luminance ratio will produce images of large contrast, although processed to a small gamma. It is true, however, that contrast will increase with increasing gamma providing the images fall on the straight line portion of the characteristic curve.

In order to solve this gamma vs. contrast dilemma, the use of a contrast index has become popular. Whereas, gamma is based upon an exact straight line, the contrast index only considers the average slope or the slope of a line drawn between two distinct points on the characteristic curve. A contrast index meter, shown in Figure 86 is used to determine the index number. This transparent meter is placed over the H & D curve so that the curve intersects the same value on both circular arcs. That value is known as the contrast index. Although this index serves the same purpose as gamma, i.e., processing control, it is often more valid since many films either contain no straight line portion or contain more than one straight line.

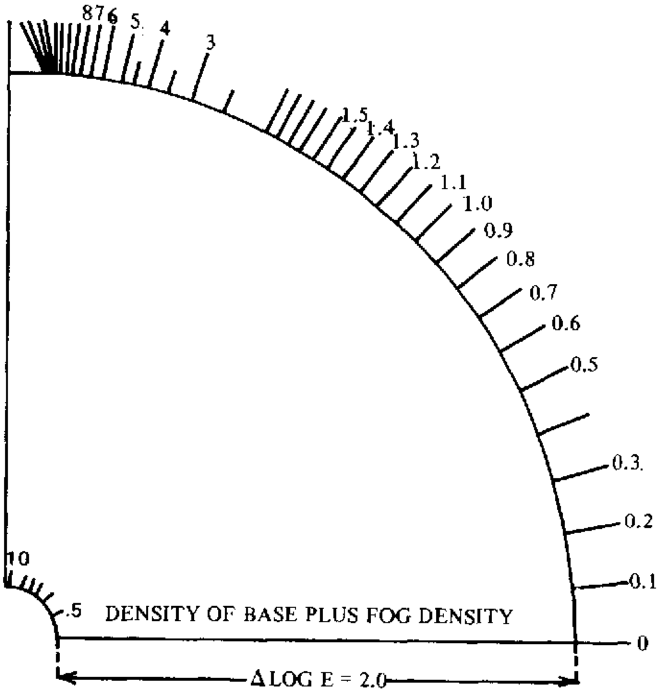


Figure 86. Contrast index meter.

6.3.3 Time-Gamma and Time-Temperature Charts

Several useful processing controls can be established by developing a series of sensitometric wedges under pre-determined conditions. At least five wedges are exposed onto separate pieces of film and developed at the same temperature and agitation with the only variable being the time of development. These times should cover the range from very short (say, two minutes) until infinity gamma is reached (say, twenty minutes). Beyond infinity gamma, only the base plus fog level of the film increases. The H & D curves for each development time are plotted on the same graph as in Figure 85.

A time-gamma curve is then generated by plotting the development time along the x axis and the resultant gammas obtained along the y axis. Such a curve will permit the selection of the particular processing time required in order to produce a desired gamma for that particular film emulsion. An example of the time-gamma curve is shown in Figure 87, together with the set of H & Dcurves used to geenrate it.

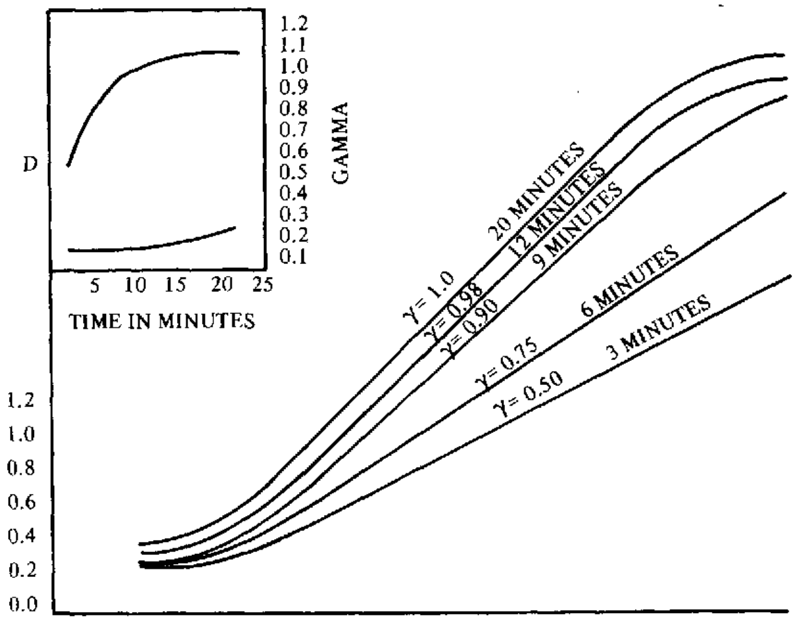


Figure 87. Plotting time-gamma and time-fog curve.

Another useful graph derived from the family of H & D curves is called a time-temperature chart. To construct a time-temperature plot, the following procedures are used:

- Plot a family of H & D curves at a specific agitation and temperature (say, 65°F) varying only the development time as described previously. Generate a time-gamma curve.
- Repeat the process using the same chemistry and agitation, but a new temperature (say, 75°F).
- Set up a graph (on semi-log paper) with temperature plotted along the y axis and time in minutes along the x axis.
- Select a value for gamma on the 65°F time-gamma curve and plot the processing time required to achieve that gamma.
- For the *same* value of gamma, determine the processing time from the 75°F time-gamma curve. Plot this point on the time-temperature chart. Connect the two points with a straight line.
- Repeat this process for each value of gamma desired.

Such a chart permits one to select the processing temperature, as well as the time which is necessary to produce a specific gamma on the film. Figure 88 illustrates the resultant time-temperature chart. Although time-gamma curves and time-temperature charts are supplied by film manufacturers, they only indicate the recommended gammas for ordinary photographic applications. Precision photographic experiments, however, often require large departures from the ordinary and such supplied manufacturer's data would be of no value.

By referring subsequent characteristic curves to the gamma variable plots, the processor can monitor his development schedule. Any displacement in the subsequent curves would show that a change has occurred in the processing. The direction of the shift and the record of the particular processing operation will give some indication of the factor causing the change. In the case of routine processing, generation of an occasional characteristic curve should suffice to warn of any change in the processing. For critical processing, however, test strips should be run and read prior to the actual film development. In additon, exposed (but not processed) test strips may be fixed to the beginning and end of both hand and machine-processed films. This yields a record of any change occuring during processing, i.e. from the beginning of the roll to the end. All such test strips must naturally be of the same film type as that being processed (and from the same lot number, if possible). These step wedges should also be given the sensitometric exposure that best approximates those received by the film to be processed.

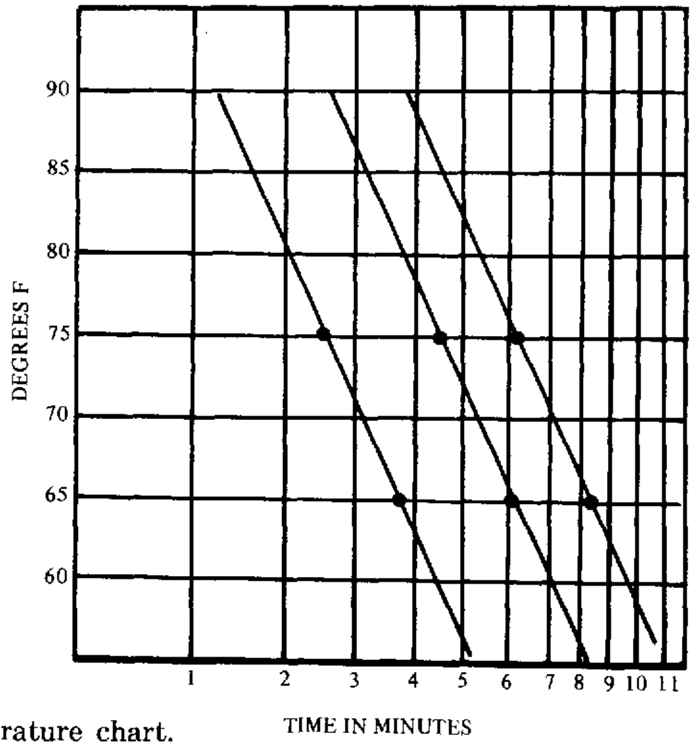


Figure 88. Time-temperature chart.

It has been stated that the degree of agitation during development has marked effect upon the quality of the final image. Although increased agitation will increase the slope or gamma of the characteristic curve (as in the case of time and temperature), the most significant effect that agitation has is upon the shape of the characteristic curve. Six identical films which have been given the same exposures and processed to the same gamma using different agitation schedules will show curves with shoulder portions having substantial deviation, as shown in Figue 89. These deviations, if uncontrolled, represent what would constitute an unpredictable distortion in the tonal values of the final film record. If no agitation is given, muddy and uneven highlights must result in the final picture.

6.4 Reciprocity Law and Reciprocity Law Failure

The basic equation for the exposure of images onto a photographic emulsion has been shown to be:

$E = I(t)$ where I is the illumination and t is the exposure time.

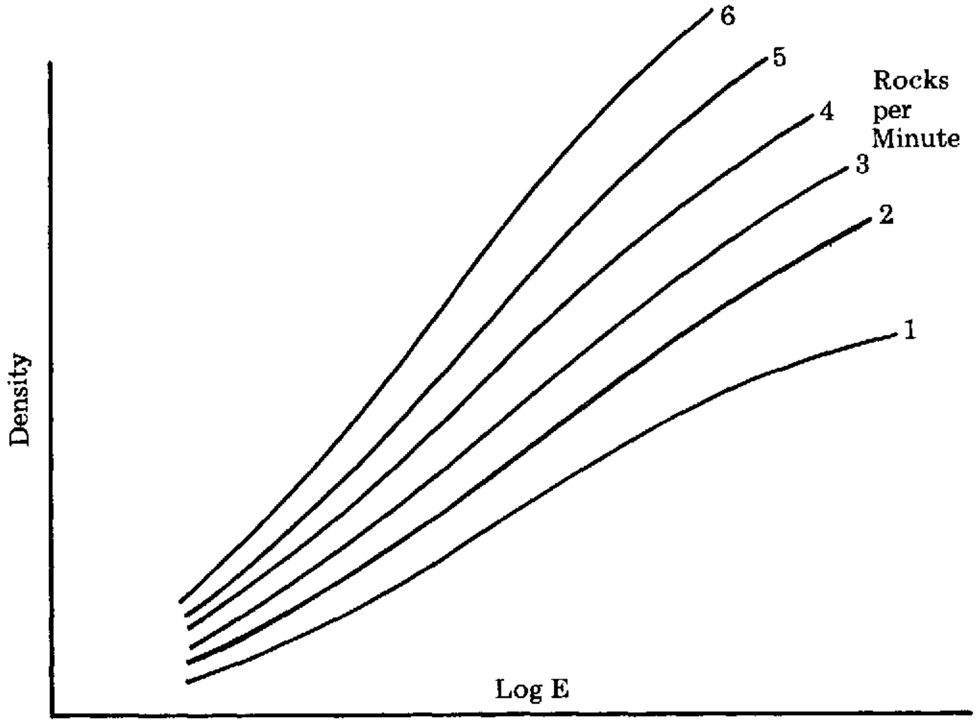


Figure 89. Effects of agitation upon the characteristic curve.

The reciprocity law states that the density of the image formed is dependent *only* upon E and not upon the components of the equation, I or t. Experimentation has shown, however, that although E remains constant, changes in I or t will produce images which are considerably different. This fact is known as reciprocity law failure. To study the effect of I and t upon the resultant image density, a series of reciprocity law failure curves are generated. Sensitometric tests are made in which both I and t are varied, while the total exposure E remains constant. It should be noted that conventional sensitometers do not possess the required flexibility to produce reciprocity law failure data. Hence, this information is supplied by the film manufacturers and takes the form of that shown in Figure 90. The reciprocity failure curves are usually symmetric for a considerable illumination range in the vicinity of the minimum point; deviations, however, increase at both high and low intensity values. If no reciprocity failure existed, then the curves would become horizontal lines. One should note that the shallowness of the curves does not indicate that reciprocity failure is slight. The data is plotted on log-log paper and so there is considerable flattening of the curves. The exposure intensity (I), for maximum efficiency, is that value which produces a medium density (say, 1.5) within the exposure time (t) range of .1 and 10 seconds.

Referring to Figure 90, any vertical line represents a constant intensity. To determine the constant time lines at 45°, the following procedure is used:

- Locate on the graph, the point (log I = -2.0, log E = -2.0). Also locate the point (log I = 1.0, log E = 1.0).
- Draw a 45° line connecting the points. This line is the constant time line for one second exposure.
- Locate the point (log I = -2.0, log E = -1.0) and the point (log I = -1.0, log E = 0). Connect the points. This line, also at 45°, represents a constant time line for ten seconds.
- Locate the point (log I = 2.0, log E =0) and the point (log I = 3.0, log E = 1.0). Connect the points. This line at 45° represents a constant time line of 100 seconds.

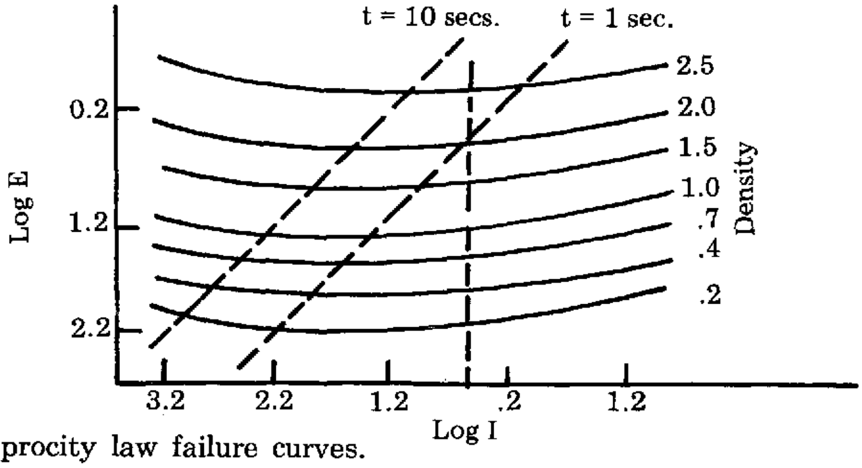


Figure 90. Reciprocity law failure curves.

- Repeat the procedure for as many time lines as are required. Reciprocity law failure data must be obtained by extenive sensitometric tests on the film since it cannot be predicted from either theory or emulsion characteristics. Hence, it is strongly recommended that the user consult the manufacturer's data sheets for the reciprocity characteristics of a film. This data is usually much more reliable than the reciprocity curves which are generated in the average photo lab.

6.5 Summary

- Relative log exposure curves consist of plotting the densities of a step wedge exposed onto a test film against the densities of the original wedge.
- Log exposure curves consist of plotting the densities of a step wedge exposed onto a test film against the logarithms of the photographic exposures which created those densities.
- The log E values for the exposed step wedge are determined by taking the log of the maximum exposure minus the densities of the original wedge.
- Log exposure curves are also known as H & D or characteristic curves.
- Increasing the step wedge exposure will shift the H & D curve to the right.
- H & D curves have four major regions: toe, straight line, shoulder, and reversal region.
- Most photography is taken so as to place the imagery on the toe or straight line.
- Film speed depends upon the gamma of the characteristic curve, as well as the density level at the point of measurement.
- Gamma is a measure of the processing conditions under which the film was developed.
- Contrast is not to be equated with gamma.
- Straight line portion of characteristic curve is greatest for low gamma.
- Gamma or slope of the H & D curve increases with increasing development time, agitation, and solution temperatures.
- Contrast index is used instead of gamma when no true straight line portion exists on the characteristic curve.
- Time-gamma curves indicate the development time required to produce a particular gamma on the film.
- Time-temperature charts permit the selection of both development time and solution temperature in order to achieve a particular gamma on the film.
- Reciprocity law failure curves indicate the source intensity and exposure time required to produce a particular density on the emulsion.

CHAPTER 7

NEGATIVE EXPOSURE AND PROCESSING

OF MULTISPECTRAL BLACK—AND—WHITE PHOTOGRAPHY

Chapter 1 discussed briefly the concept of additive or multispectral photography; no attempt was made to describe the exact procedure which must be followed if meaningful imagery is to result. This is the subject of Chapters 7, 8, and 9.

To produce a multispectral additive color photograph of a scene requires four distinct tasks:

- The analysis of color dissection of the scene. This involves the choice of optimal photographic components (including camera lenses, spectral filters, and black-and-white films) selected specifically to maximize the detection of *particular* ground objects. Often two or more sets of these components are used in a single photo mission, especially if one set will not adequately differentiate between all the targets of interest.
- The development of the black-and-white negatives. This process includes determining the best negative contrast in order to include the entire scene brightness range on the straight line portion of the characteristic curve. Filter and film selection, as well as exposure and processing conditions will be discussed in this chapter.
- Chapter 8 specifies the requirements for printing the black-and-white multispectral transparencies. This involves the correct exposure and processing conditions so as to produce high image brightness and color saturation in the additive color viewer. In this stage, correction is also made for inherent differences in contrast between the multispectral records caused by the dominant wavelength of the camera filters.
- The synthesis or recombination of the black-and-white positive transparencies in the additive color viewer is the subject of Chapter 9. This includes alterations in the hue, brightness, and saturation of each multispectral record in order to maximize the color difference between one or more classes of objects.

Though the procedures outlined in the following sections may at first appear somewhat complex, excellent multispectral results should be obtained by taking such precautions.

7.1 Considerations in the Selection of Film and Exposure for Use in Multispectral Photography

Of all the factors which affect the final outcome of a multispectral photographic mission including camera exposure, film emulsion, and the processing-printing conditions, the most important are the spectral filters used in conjunction with each multispectral lens. Providing that accurate ground spectroradiometric data has been obtained, the task of filter selection is rather straight-forward. If, however, no such data is available, then one must resort to recommendations provided by other investigators (as reported, for example, in the scientific literature). For detection of *subtle* phenomena, this will amount to no more than a best guess and meaningful multispectral imagery probably will not result. It will be assumed, for this discussion, that spectroradiometric data will be taken for a particular target type embedded in a single background.

7.1.1 Spectroradiometric Reflectance Spectra

In situ spectroradiometric measurements provide the photographer with the data necessary to select an optimal set of multispectral camera filters. Two types of spectra can be measured on any target — perceived and inherent. Perceived spectra are obtained using only a reflectance radiometer and represent the spectral distribution of the target as modified by the quality of the illuminant. The inherent spectra, on the other hand, represents the color distribution of objects *without* the biasing effect of the illuminant. Inherent spectra are obtained by measuring not only the perceived spectra of the object, but also the distribution of the incident illumination. To accomplish the task of measuring inherent spectra, two spectroradiometers are required. The first, a reflectance unit, has a telescope in front of the monochromator to focus on and to collect the reflected radiation from a particular target area. The incidence radiometer measures the total downwelling global radiation (sun and skylight) over a hemispheric solid angle of 2π steradians by means of a translucent disc placed over the collecting aperture.

Each spectroradiometer usually has two separate photodetectors (one for the visible spectrum and one for the IR) which are interchanged at some point during the measurement. Because of this time delay between the start and end of each scan and because cloud or haze conditions may change during the measurement cycle, the incident and reflected radiation data for any given wavelength *must* be taken simultaneously. In other words, the incident and reflectance monochromators are set at a particular wavelength and this data is recorded. The process is repeated for each value of wavelength to be measured. If, however, the solar angle is high and the atmosphere is clear, then the incident and reflectance spectra need not be taken simultaneously. A difference of a few minutes between the spectra will not seriously affect the results under these conditions.

Filter selection is based upon determination of the inherent spectra of ground objects and two methods will be presented. The first is based upon a statistical analysis of the spectra, while the second merely examines the regions of color difference in order to predict the tonal values which will result with the use of a particular emulsion.

One set of spectroradiometric data for the target and one set of data for the background is insufficient for the proper analysis of the spectral differences between the two. The accuracy of the data is greatly increased by obtaining many sets of such spectra, although four is considered to be the minimum number required; that is, four sets (each including incidence solar illumination and reflected radiation measurements) are necessary for *both* the target and its background. What is desired, then, consists of measuring the solar illumination four times, as well as measuring *four separate areas* of the target (*not* the same area four times). In situ measurements of the target reflectance spectra must be made from observation situations which maximize the uniformity of the target; that is, target areas are selected which do not contain: (a) large amounts of unwanted background objects, or (b) large amounts of shadowed areas. Of these two categories, the former is more serious since it introduces drastic errors into the target reflectance *distribution.* Shadowed areas merely decrease the amplitude of the spectra. If one is presented with a choice between (1) an object (say, foliage) which is evenly illuminated, but contains other unwanted objects (e.g., bark, soil, etc.) or, (2) an object (foliage) *unevenly* illuminated, but having no unwanted objects in the measuring field, the latter should be selected.

Referring to Figure 91, the percent directional reflectance or inherent spectra is measured in the following way:

(a) The dark current, for both the incidence and reflectance photo detectors, is measured prior to the spectral scan of the object and is recorded in Columns 2 and 3 as DC1.

Site: ________

Target: ________

Date: ________

Instrument: ________

Ground Truth Sheet #: ________

Time: ________

Weather: ________

By: ________

SPECTRORADIOMETRIC DATA SHEET

Starting Dark Current (DC1)	Scan #1				Scan #2				Scan #3				Scan #4				Reflectance Data (Decimal)				
	( )		( )		( )		( )		( )		( )		( )		( )		Scan #1	Scan #2	Scan #3	Scan #4	Average
	Incidence		Reflec.		Incidence		Reflec.		Incidence		Reflec.		Incidence		Reflec.		$\left(\frac{R-DC}{I-DC}\right)$	$\left(\frac{R-DC}{I-DC}\right)$	$\left(\frac{R-DC}{I-DC}\right)$	$\left(\frac{R-DC}{I-DC}\right)$	$\left(\frac{R}{I}\right)$
	I	I-DC	R	R-DC	I	I-DC	R	R-DC	I	I-DC	R	R-DC	I	I-DC							
380 400 425 450 475 500 525 550 575 600 625 650 675 700 725																					
Ending Dark Current (DC2)	( )		( )		( )		( )		( )		( )		( )		( )						
DCV=$\frac{(DC2+DC1)}{2}$	DCV= ( )		DCV= ( )		DCV= ( )		DCV= ( )		DCV= ( )		DCV= ( )		DCV= ( )		DCV= ( )						
Starting Dark Current (DC3)	( )		( )		( )		( )		( )		( )		( )		( )						
750 775 800 825 850 875 900 925 950 975 1000																					
Ending Dark Current (DC4)	( )		( )		( )		( )		( )		( )		( )		( )						
DCIR=$\frac{(DC3+DC4)}{2}$	DCIR= ( )		DCIR= ( )		DCIR= ( )		DCIR= ( )		DCIR= ( )		DCIR= ( )		DCIR= ( )		DCIR= ( )						

Figure 91. Spectroradiometric Data Sheet.

(b) Beginning at about 380 nms, the incident and reflectance spectra are measured and recorded as I and R in Columns 2 and 3.

(c) At the end of the visible scan, the dark current of each detector is again measured and recorded as DC2.

(d) At about 700-750 nm, the visible photodetectors will generally have to be interchanged with the infrared sensitive detectors. Care must be taken that these tubes are disconnected from the power supply before they are separated from the monochromator housings.

(e) The dark current for both the incident and reflectance infrared photodetectors is measured and recorded as DC3.

(f) The near infrared incident and reflectance spectra are measured and the ending dark current is recorded as DC4.

(g) This concludes the spectral measurements required for Scan #1.

(h) The reflectance spectroradiometer is now aimed at a different part of the same target, care being taken to avoid unwanted backgrounds in the field of view.

(i) Steps (a) through (f) are repeated for Scan #2, Scan #3, and Scan #4.

(j) The average visible dark current for *each* scan is computed as: DCV = (DC1 + DC2)/2. The average infrared dark current for *each* scan is computed as: DCIR = (DC1 + DC2)/2.

(k) Step (j) is repeated for both the incident and reflectance spectroradiometers for each scan.

(l) The measured spectra (both incident and reflectance) are reduced by the average values of the dark currents and are recorded as either (I-DC) or (R-DC).

(m) The reflectance of the object (for, say Scan #1) is computed as: (R-DC)/(I-DC). This quantity is a decimal and may be converted to percent directional reflectance (PDR) by multiplying by 100.

(n) At each wavelength, the decimal reflectances for all scans are averaged and entered into Column 14 of Figure 91.

(o) Assuming that correction curves have been generated to account for both the incident and reflectance photodetector responses (see Chapter 4), the quotient $C = C_R/C_I$ is generated for each value of wavelength. (C_R is the reflectance spectroradiometric correction factor at any λ and C_I is the incidence spectroradiometric correction factor at the same λ).

(p) This set of C's is multiplied by the final average decimal reflectances, Reflectance $\lambda = (R_\lambda/I_\lambda)C_\lambda$

(q) The last column of Figure 91 indicates the *target* average spectral reflectance over the visible and near-infrared regions. A similar set will exist for the background spectra associated with the target. These average reflectances are then plotted against wavelength as shown typically in Figure 92.

Photographic emulsions are not sensitive beyond 950 nm so that usually there is no need to measure the spectra beyond this point, although most radiometers will measure up to 1500 nm. Also, the wavelengths associated with Figure 91 may require modification depending upon the spectral bandwidth of the radiometer. The more expensive units contain a series of entrance and exit slits which will vary the bandwidth from about 25 nm to 5 nm. The accuracy of the data will, naturally, be increased as the bandwidth is decreased (i.e., the number of wavelengths at which data is taken increases).

At this point, one can either examine the target and background spectra statistically or in terms of the inherent amplitude differences as a function of wavelength. This choice is usually dependent upon the length of time available for analysis prior to flight.

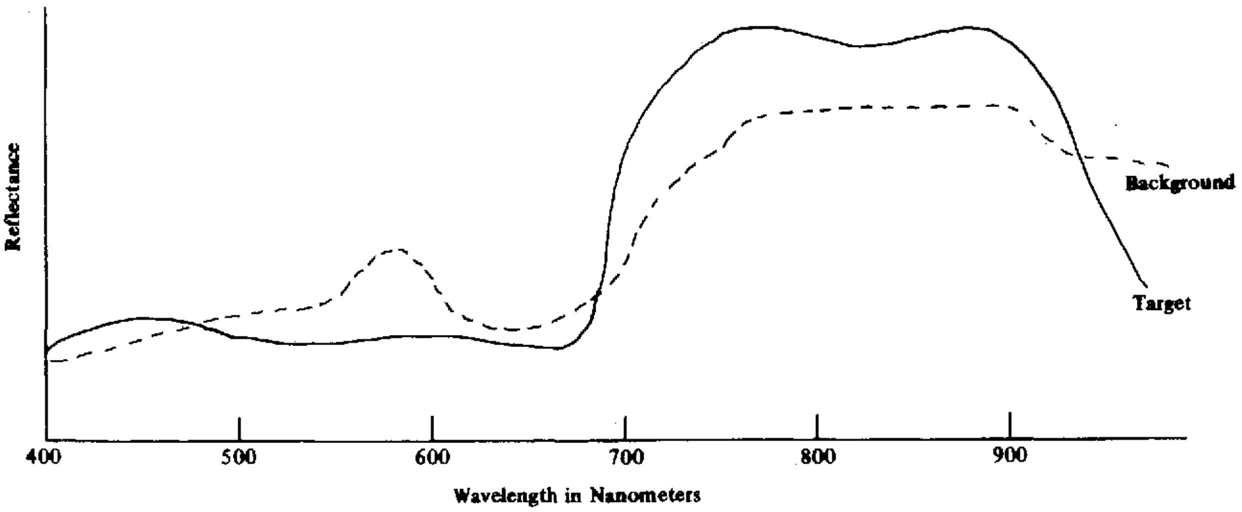


Figure 92. Typical average spectral reflectance curves for a group of targets and backgrounds.

The statistical analysis of spectra and the results produced will depend largely upon the assumptions which are made concerning the distributions of the data (spectral reflectances). Suppose, for example, that a very large number of spectra are taken for a particular target (say, fifty sets). After plotting all fifty sets, most of the curves are pretty well grouped together on the graph, although a few are higher or lower than this main group (see Figure 93).

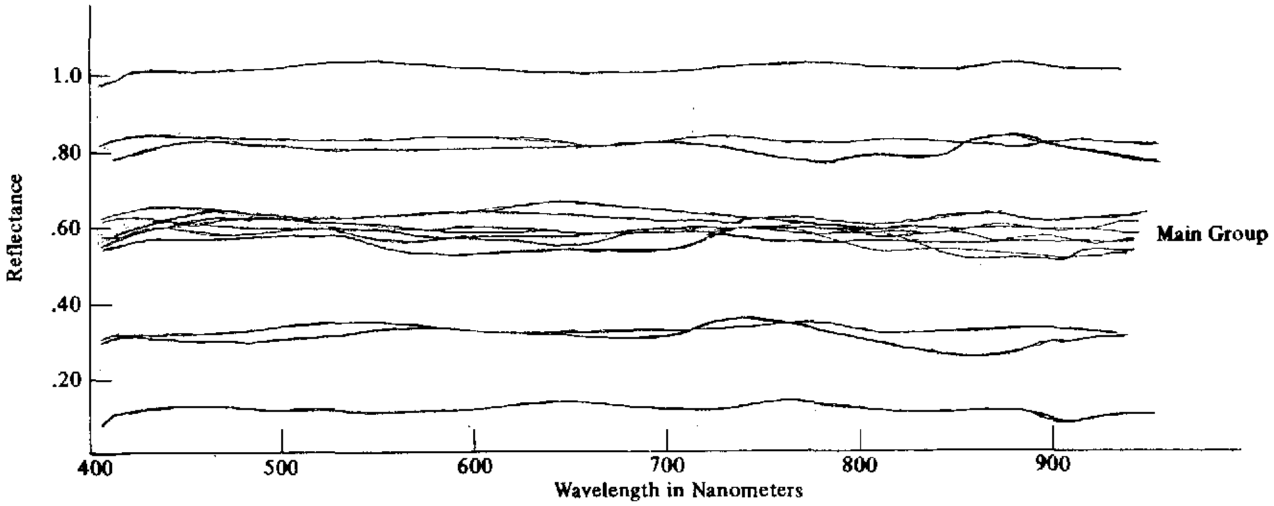


Figure 93. Spectral reflectance of individual target cluster about a single average reflectance value, although some targets have values greater or lower than this mean.

If a plot is made of the average reflectance vs. the number of spectral curves at that value, the distribution might look like Figure 94. Notice that this curve is rather symmetric, the number of spectra *above* the mean being about the same as those *below* the mean. Such a group of spectral reflectance data (Figure 94) is then said to be *normally* distributed. If one had plotted a large number of spectra from random targets (of the same type, naturally) and had noticed that the general patterns of Figures 93 and 94 were present, there would be no further need to question the nature of the distribution — it would be firm and fixed as being normal. However, a definite assumption of this type is invalid when plotting a small number of spectra — in our case, a minimum of four. It may well

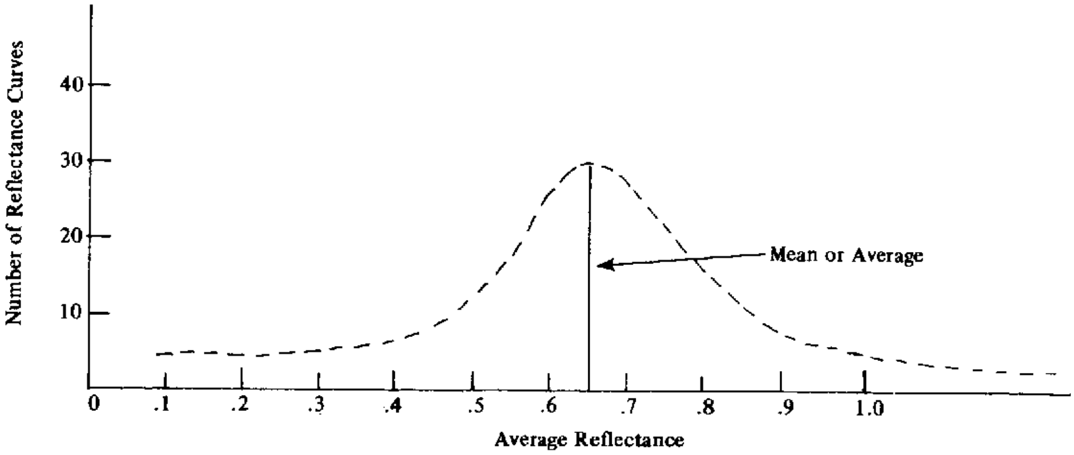
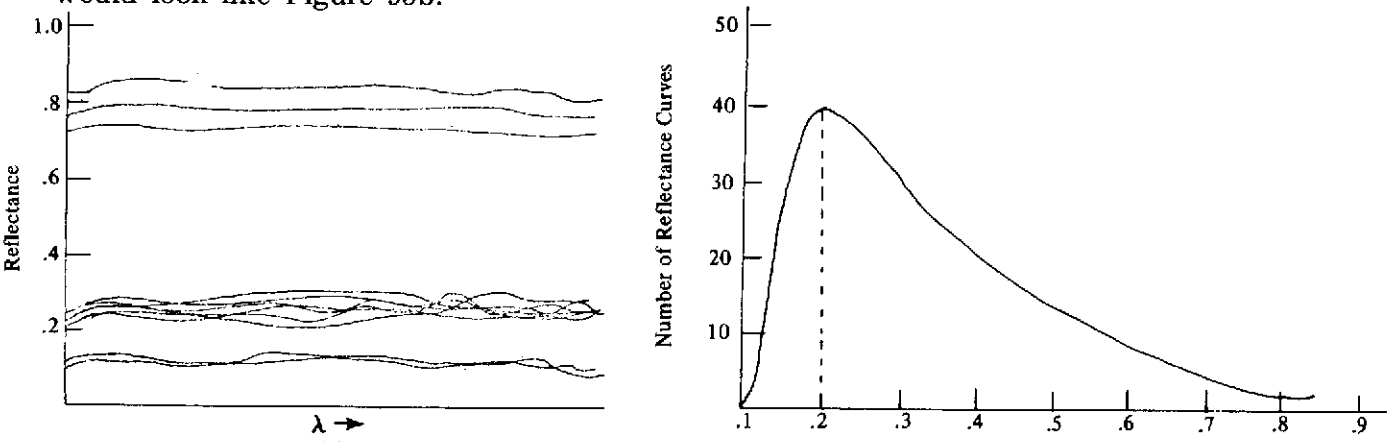


Figure 94. Distribution of target reflectances shown in Figure 93 indicates that they are normally distributed.

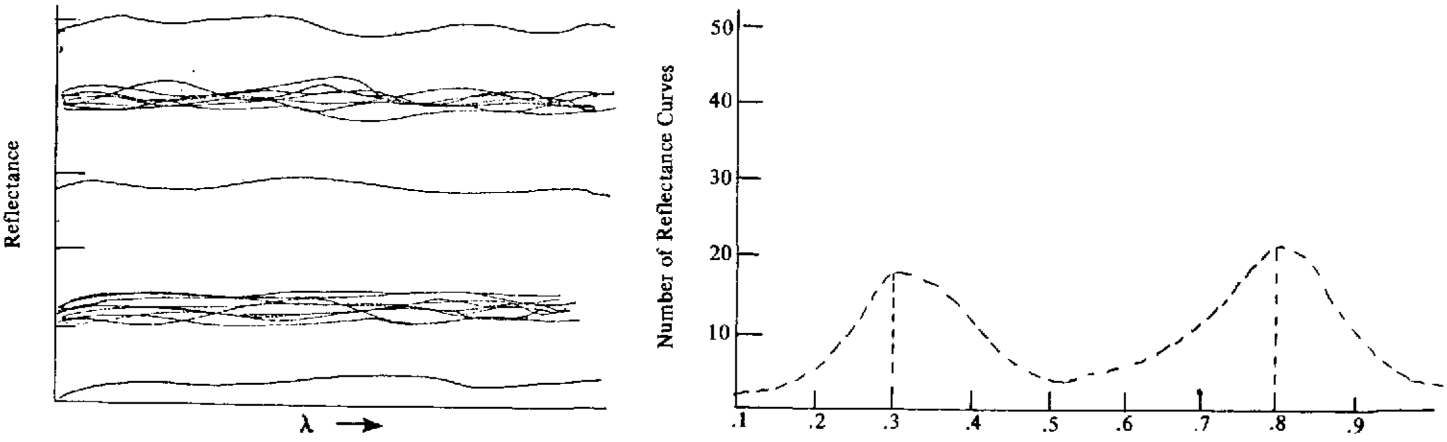
happen that the distribution of the spectra is *not normal.* Returning again to our theoretical fifty sets of spectra, one may notice that they are grouped as in Figure 95a and the resultant distribution curve would look like Figure 95b.



(a)

(b)

Figure 95. Reflectance of individual targets; the distribution of the data shows that it is *not normal.*



(a)

(b)

Figure 96. Reflectance of individual targets which do not follow a normal distribution.

Or, perhaps, the data would be grouped as in Figure 96a. In this case, the non-normal distribution of Figure 96b would result.

These two examples illustrate the concept of non-normal distribution. The dilemma, therefore, is as follows: If one *cannot* necessarily assume that the spectra has a normal distribution, what assumption *can* be made? The answer lies in the performance of *two* different statistical tests on the same sets of target and background spectra:

- The first is a t-test based upon the assumption that the spectra *is* normally distributed.
- The second is a non-parametric Mann-Whitney test which makes *no assumptions as to distribution of the spectra at all.*

These two statistical tests will cover all contingencies and their results will obviously differ. If, however, one compares the results of both tests and selects *only* those spectral regions which are significant in both tests, then obviously one may use those filtered regions with confidence in a multispectral camera. By way of illustration, suppose the results of the t- and Mann-Whitney tests indicate the following blacked in spectral regions as being useful in detecting a target from its background (Figure 97).

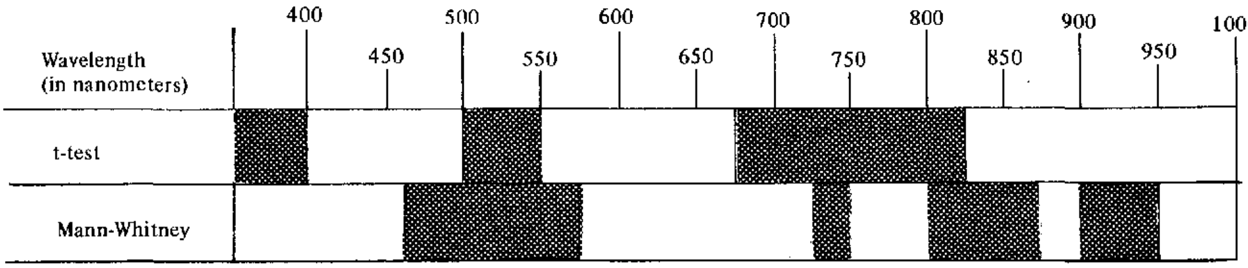


Figure 97. Example of useful spectral regions as determined by statistical analysis of reflectance data.

One would then select those wavelength intervals which are common to both tests, namely:

- 500 to 550 nm
- 730 to 750 nm
- 800 to 825 nm

and would purchase multispectral filters which covered these regions.

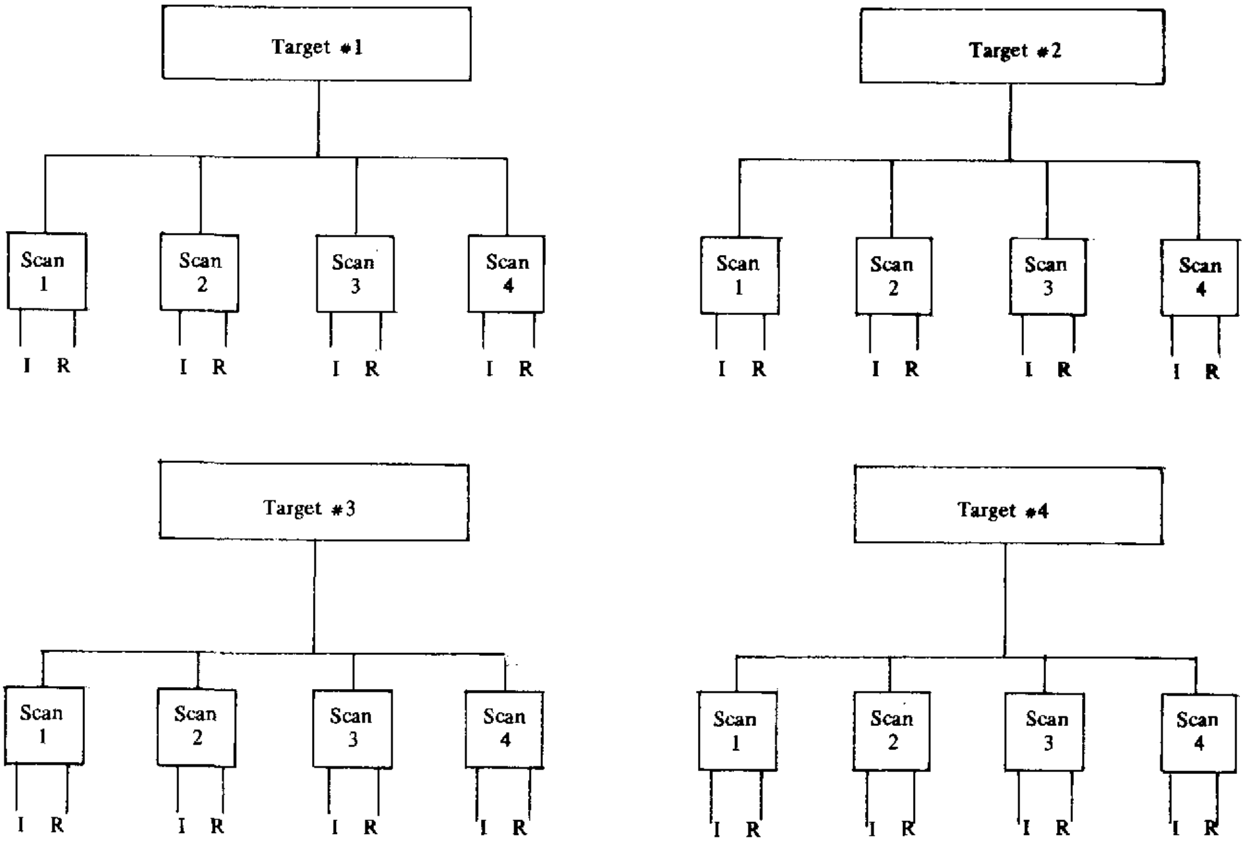
Step-by-step procedures are now given for the computation of both the t-test and Mann-Whitney test. No attempt here is made to present theoretical considerations; the reader is referred to the text by R.P. Runyon and A. Haber entitled *General Statistics* and also the text by W.J. Conover entitled *Practical Non-Parametric Statistics*, for a detailed discussion of these tests.

7.1.2 Statistical Analysis of Reflectance Spectra

It will be recalled that one set of spectra for a *given* target must consist of at least four scans. However, at least four *targets* of the same type should be measured for the statistical validity of the analysis. In other words, for any target type (for example, red spruce trees), four targets (individual trees) should be measured four times (four scans). The total number of spectral reflectance sets then consists of:

Target = 4 samples x 4 scans = 16 data sets

Each data set consists of an incidence and reflectance measurement so that the minimum number of spectra per target or background type is 32, as shown in Figure 98.



I = Incident Spectroradiometric Data
R = Reflectance Spectroradiometric Data

Figure 98. Minimum number of spectral sets per target type is 32.

t-Test Computation

Assume:

- Four targets of the same type given number designations, say 1, 2, 3, 4, etc.
- Four scans/target
- Twenty-seven wavelength points
- Four backgrounds of same type, given number designations, say, 5, 6, 7, 8.
- Four scans/background

1. Compute average reflectances of four scans for each of the four targets and four backgrounds (use Figure 91) for all wavelengths. Call these $\bar{R}_{\lambda n}$ where the subscript n indicates the designation number.
2. For *targets*: at each value of wavelength (λ), average the four reflectances resulting from step 1. Call them $\bar{R}_{\lambda T}$.
3. Repeat step 2 for the *backgrounds*. Call these averages $\bar{\bar{R}}_{\lambda B}$.
4. Compute sigma squared for the targets at *each* wavelength as:

$$\sigma_T^2 = \frac{(R_{\lambda 1} - \bar{\bar{R}}_{\lambda T})^2 + (R_{\lambda 2} - \bar{\bar{R}}_{\lambda T})^2 + (R_{\lambda 3} - \bar{\bar{R}}_{\lambda T})^2 + (R_{\lambda 4} - \bar{\bar{R}}_{\lambda T})^2}{3}$$

where $\bar{\bar{R}}_{\lambda T}$ = average of the $\bar{R}_{\lambda T}$'s

or:

$$\sigma_T^2 = \frac{\sum_{n=1}^{N_T} (\bar{R}_{\lambda n} - \bar{\bar{R}}_{\lambda T})^2}{N_T - 1}$$

where N_T is the total number of targets.

5. Compute sigma squared for the backgrounds at each λ as:

$$\sigma_B^2 = \frac{(\bar{R}_{\lambda 5} - \bar{\bar{R}}_{\lambda B})^2 + (\bar{R}_{\lambda 6} - \bar{\bar{R}}_{\lambda B})^2 + (\bar{R}_{\lambda 7} - \bar{\bar{R}}_{\lambda B})^2 + (\bar{R}_{\lambda 8} - \bar{\bar{R}}_{\lambda B})^2}{3}$$

where $\bar{\bar{R}}_{\lambda B}$ = average of the $\bar{R}_{\lambda B}$'s

or:

$$\sigma 2 = \frac{\sum_{n=1}^{N_B} (\bar{R}_{\lambda n} - \bar{R}_{\lambda B})^2}{N_B - 1}$$

where N_B is the total number of backgrounds.

6. Compute degrees of freedom, ν:

$$\nu = \left[\frac{(\sigma_T^2/N_T + (\sigma_B^2/N_B)^2}{\frac{(\sigma^2/N_T)^2 (\sigma^2/N_B)^2}{(N_T + 1) + (N_B + 1)}} \right] - 2$$

7. Compute statistic, t' =

$$t' = \frac{\bar{\bar{R}}_{\lambda T} - \bar{\bar{R}}_{\lambda B}}{\left[\frac{\sigma_T^2}{N_T} \quad \frac{\sigma_B^2}{N_B}\right]^{1/2}}$$

Mann-Whitney Computation

The same assumptions are made concerning the data for the Mann-Whitney statistical test, i.e., four targets and four backgrounds. The percent reflectance, which has already been computed, is again used. The procedure for performing the Mann-Whitney test is as follows.

(a) For a given wavelength (λ), the reflectances of *both* the target and backgrounds are listed in ascending order. Place a T after the target reflectances and a B after the backgrounds so that you can keep track of which group each value belongs in. Assign a rank to each.

(b) Find the sum of ranks for backgrounds and sum of ranks for targets as shown above; call them R_B and R_T respectively.

(c) Compute the U statistic: $U = N_T N_B + \frac{N_T(N_T+1)}{2} = R_T$

(d) Compute the U' statistic: $U' = N_T N_B - U$

(e) Find values for U and U' in a Mann-Whitney statistical table for the confidence limits of 60%, 70%, 80%, 90%, and 95% as shown in Table X for the confidence limit of 95%.

(f) The process of reordering the reflectance according to its ranks is repeated for all values of wavelength. An example of rank assignment is given below.

Rank	$\bar{R}_\lambda$	Background Ranks	Target Ranks
1	36.2 (B)	1	3
2	41.0 (B)	2	4
3	43.5 (T)	5	7
4	49.7 (T)	6	8
5	61.2 (B)	Sum = 14 = R_B	Sum = 22 = R_T
6	61.8 (B)		
7	69.0 (T)		
8	71.8 (T)		

7.1.2.1 Filter Selection From Statistical Analysis of Spectra

The computation of both the t and Mann-Whitney statistical tests is often difficult to perform by hand. They should, therefore, be computer programmed especially if large quantities of data are to be reduced. Often computer companies have such sub-routines already available for users at their installations. Long Island University has these and other statistical tests for analysis of spectra programmed for several large computers and can be called upon for any assistance.

Once the statistical analyses have been performed for the target and background groups of spectra, the selection of an optimal set of filters is rather straightforward. The result of the t-test analysis produced two values, the degrees of freedom ν and the statistic t'

Look up the t-distribution (Table XI) in a statistical handbook. For the computed value of ν, there will exist values for t at different confidence limits. Select a confidence limit, say 60%, and find the value for t. If $|t'| > t$, then target and background groups are the same at that wavelength. Construct a data sheet listing all values of wavelength and whether the groups were the same or different at 60% confidence. Refer to Table XII.

Select another confidence limit, say 80%, and again test for groups being the same or different. Record whether the groups were the same or different at 80% on the same data sheet. The higher the confidence limit, the surer we are that there does exist a difference between the backgrounds and targets at that wavelength. This testing must be done at each wavelength and at several confidence limits, the results being recorded on the same data sheet. Generally, 60%, 80%, 90%, 95%, and 98% confidence limits are used and it follows that the groups may be classified as *different* at the 60% limit, but the *same* at the 90% limit.

Critical Values of U_1 and U_2 for a One-tailed Test at = 0.05 or a Two-tailed Test at = 0.10

To be significant for any given n_1 and n_2: Obtained U must be equal to or less than the value shown in the table. Obtained U^1 must be equal to or greater than the value shown in the table.

N_B \ N_T	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	0 19	0 20
2	--	--	--	--	0 10	0 12	0 14	1 15	1 17	1 19	1 21	2 22	2 24	2 26	3 27	3 29	3 31	4 32	4 34	4 36
3	--	--	0 9	0 12	1 14	2 16	2 19	3 21	3 24	4 26	5 28	5 31	6 33	7 35	7 38	8 40	9 42	9 45	10 47	11 49
4	--	--	0 12	1 15	2 18	3 21	4 24	5 27	6 30	7 33	8 36	9 39	10 42	11 45	12 48	14 50	15 53	16 56	17 59	18 62
5	--	0 10	1 14	2 18	4 21	5 25	6 29	8 32	9 36	11 39	12 43	13 47	15 50	16 54	18 57	19 61	20 65	22 68	23 72	25 75
6	--	0 12	2 16	3 21	5 25	7 29	8 34	10 38	12 42	14 46	16 50	17 55	19 59	21 63	23 67	25 71	26 76	28 80	30 84	32 88
7	--	0 14	2 19	4 24	6 29	8 34	11 38	13 43	15 48	17 53	19 58	21 63	24 67	26 72	28 77	30 82	33 86	35 91	37 96	39 101
8	--	1 15	3 21	5 27	8 32	10 38	13 43	15 49	18 54	20 60	23 65	26 70	28 76	31 81	33 87	36 92	39 97	41 103	44 108	47 113
9	--	1 17	3 24	6 30	9 36	12 42	15 48	18 54	21 60	24 66	27 72	30 78	33 84	36 90	39 96	42 102	45 108	48 114	51 120	54 126
10	--	1 19	4 26	7 33	11 39	14 46	17 53	20 60	24 66	27 73	31 79	34 86	37 93	41 99	44 106	48 112	51 119	55 125	58 132	62 138
11	--	1 21	5 28	8 36	12 43	16 50	19 58	23 65	27 72	31 79	34 87	38 94	42 101	46 108	50 115	54 122	57 130	61 137	65 144	69 151
12	--	2 22	5 31	9 39	13 47	17 55	21 63	26 70	30 78	34 86	38 94	42 102	47 109	51 117	55 125	60 132	64 140	68 148	72 156	77 163
13	--	2 24	6 33	10 42	15 50	19 59	24 67	28 76	33 84	37 93	42 101	47 109	51 118	56 126	61 134	65 143	70 151	75 159	80 167	84 176
14	--	2 26	7 35	11 45	16 54	21 63	26 72	31 81	36 90	41 99	46 108	51 117	56 126	61 135	66 144	71 153	77 161	82 170	87 179	92 188
15	--	3 27	7 38	12 48	18 57	23 67	28 77	33 87	39 96	44 106	50 115	55 125	61 134	66 144	72 153	77 163	83 172	88 182	94 191	100 200
16	--	3 29	8 40	14 50	19 61	25 71	30 82	36 92	42 102	48 112	54 122	60 132	65 143	71 153	77 163	83 173	89 183	95 193	101 203	107 213
17	--	3 31	9 42	15 53	20 65	26 76	33 86	39 97	45 108	51 119	57 130	64 140	70 151	77 161	83 172	89 183	96 193	102 204	109 214	115 225
18	--	4 32	9 45	16 56	22 68	28 80	35 91	41 103	48 114	55 123	61 137	68 148	75 159	82 170	88 182	95 193	102 204	109 215	116 226	123 237
19	0 19	4 34	10 37	17 59	23 72	30 84	37 96	44 108	51 120	58 132	65 144	72 155	80 167	87 179	94 191	101 203	109 214	116 226	123 238	130 250
20	0 20	4 36	11 49	18 62	25 75	32 88	39 101	47 113	54 126	62 138	69 151	77 163	84 176	92 188	100 200	107 213	115 225	123 237	130 250	138 262

(Dashes in the body of the table indicate that no decision is possible at the stated level of significance.)

Table X

Critical Values of t

For any given df, the table shows the values of t corresponding to various levels of probability. Obtained t is significant at a given level if it is equal to or greater than the value shown in the table.

	Level of significance for one-tailed test					
	.10	.05	.025	.01	.005	.0005
	Level of significance for two-tailed test					
df	.20	.10	.05	.02	.01	.001
1	3.078	6.314	12.706	31.821	63.657	636.619
2	1.886	2.920	4.303	6.965	9.925	31.598
3	1.638	2.353	3.182	4.541	5.841	12.941
4	1.533	2.132	2.776	3.747	4.604	8.610
5	1.476	2.015	2.571	3.365	4.032	6.859
6	1.440	1.943	2.447	3.143	3.707	5.959
7	1.415	1.895	2.365	2.998	3.499	5.405
8	1.397	1.860	2.306	2.896	3.355	5.041
9	1.383	1.833	2.262	2.821	3.250	4.781
10	1.372	1.812	2.228	2.764	3.169	4.587
11	1.363	1.796	2.201	2.718	3.106	4.437
12	1.356	1.782	2.179	2.681	3.055	4.318
13	1.350	1.771	2.160	2.650	3.012	4.221
14	1.345	1.761	2.145	2.624	2.977	4.140
15	1.341	1.753	2.131	2.602	2.947	4.073
16	1.337	1.746	2.120	2.583	2.921	4.015
17	1.333	1.740	2.110	2.567	2.898	3.965
18	1.330	1.734	2.101	2.552	2.878	3.922
19	1.328	1.729	2.093	2.539	2.861	2.883
20	1.325	1.725	2.086	2.528	2.845	3.850
21	1.323	1.721	2.080	2.518	2.831	3.819
22	1.321	1.717	2.074	2.508	2.819	3.792
23	1.319	1.714	2.069	2.500	2.807	2.767
24	1.318	1.711	2.064	2.492	2.797	2.745
25	1.316	1.708	2.060	2.485	2.787	3.725
26	1.315	1.706	2.056	2.479	2.779	3.707
27	1.314	1.703	2.052	2.473	2.771	3.690
28	1.313	1.701	2.048	2.467	2.763	3.674
29	1.311	1.699	2.045	2.462	2.756	3.659
30	1.310	1.697	2.042	2.457	2.750	3.646
40	1.303	1.684	2.021	2.423	2.704	3.551
60	1.296	1.671	2.000	2.390	2.660	3.460
120	1.289	1.658	1.980	2.358	2.617	3.373
oo	1.282	1.645	1.960	2.326	2.576	3.291

Table XI

λ	60%	80%	90%	95%	98%
375	D	S	S	S	S
400	D	D	S	S	S
425	D	D	D	D	D
450	D	D	D	D	D
475	D	D	D	S	S
500	D	S	S	S	S
525	S	S	S	S	S
550	S	S	S	S	S
575	S	S	S	S	S
600	D	D	S	S	S
625	S	S	S	S	S
650	D	D	D	D	S
675	D	D	D	S	S
700	D	D	S	S	S
725	D	D	S	S	S
750	D	D	D	S	S
775	D	D	S	S	S
800	S	S	S	S	S
825	S	S	S	S	S
850	D	S	S	S	S
875	D	D	D	S	S
900	D	D	D	D	D
925	D	D	D	D	S
950	D	S	S	S	S
975	S	S	S	S	S
1000	D	D	S	S	S

S = Same, D = Different

Results of t-test spectral analysis.

Table XII

The interpretation of Table XII is obvious. The wavelengths having the highest probability of a spectral difference are the first filter choices (in this case, 425-450 nm and 900 nm). A filter peaking at 650 nm would be the next choice, while one at 750 nm would be the last selection. In practice, spectroradiometers measure smaller wavelength intervals, resulting in a much finer analyses of the spectral differences between groups. The dotted lines on Table XII give a rough indication of the possible filter bandwidths.

The same type of data sheet (at Table XII) is constructed for the results of the Mann-Whitney test. After finding the values for U_1 and U_2 in Table X, the following table is made: If $U_1 <$ U and $U_2 >$ U , then the reflectances of the two groups are considered to be the same at that wavelength. If $U_1 \geq$ U and $U_2 \leq U'$, then the reflectances of the two groups are considered to be different at that wavelength. The results of both types of statistical analyses are now compared. Wavelength intervals in which the groups are different for *both* the t- and the Mann-Whitney tests are the wisest choice. An example of such similar regions is shown in Figure 97.

7.1.3 Graphical Analysis of Spectroradiometric Data

When a computer is not available, the statistical analysis of the spectra can become too time consuming to be performed just prior to flight. Although the in situ reflectance measurements could be obtained a considerable time before the flight, the environmental phenomena may be different, resulting in a set of invalid spectra at the time of flight. Hence, a graphical analysis of the data may be the only practical method with which to choose a set of multispectral camera filters.

The percent directional reflectances of both the target and background groups must be determined as shown in the preceding section. The difference between these reflectances is then determined at each wavelength. Figure 99 shows a plot of these differences as a function of wavelength. Notice that the background group is considered as constant along the x-axis. The positive or negative deviations of the average target group from this background are plotted along the y-axis.

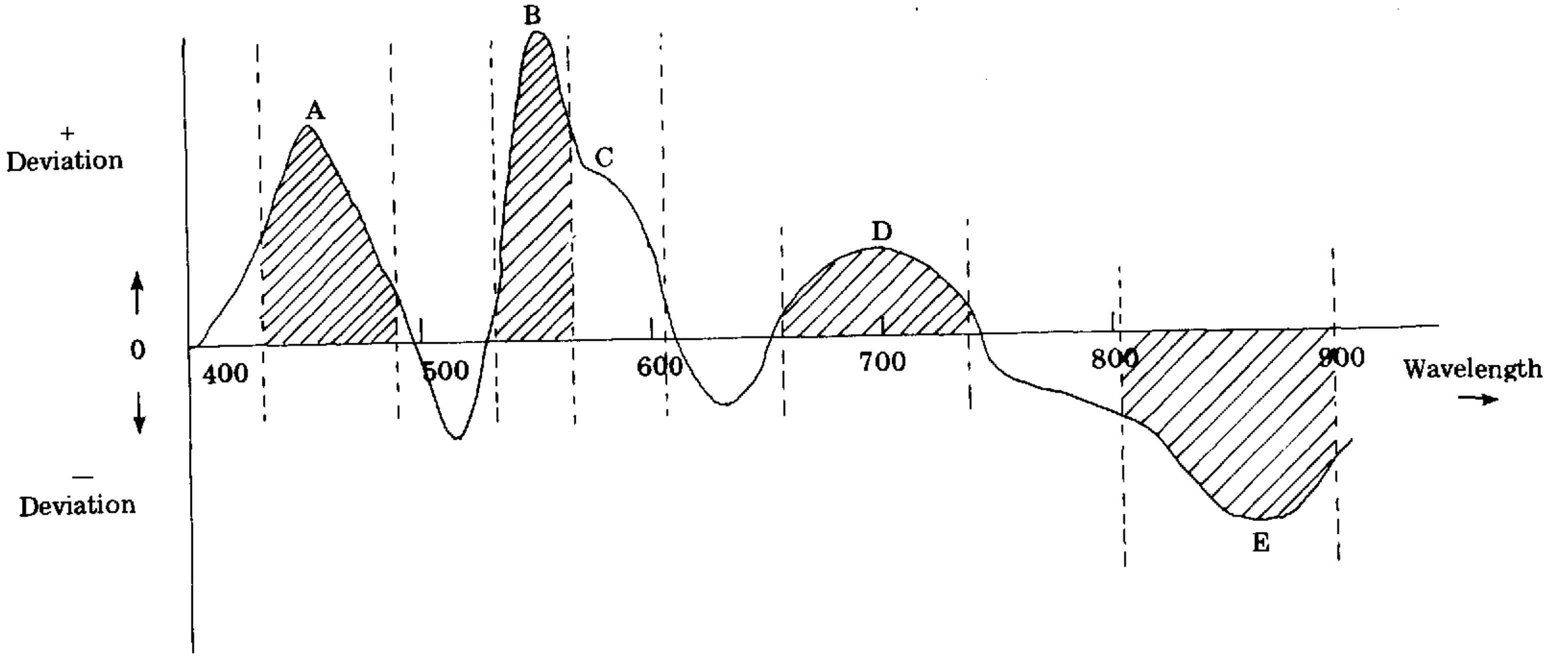


Figure 99. Graphical analysis of spectra showing deviations of target from background and candidate filter bands.

Three factors determine the wavelength intervals (or bandwidths) of the filters selected from Figure 99:

- The deviation (+ or −) from the x-axis must be as large as possible.
- The band must also be of sufficient width.
- The bands must not overlap.

Although spectral interval B possesses the greatest amplitude difference, it may not be wide enough to yield adequate exposure. However, the interval (B and C) could be selected for a filter, as well as A, D, and E. All other things being equal, two bands having a positive deviation and two bands having a negative deviation should be selected. This will result in: (a) the target being lighter than the background on two of the multispectral records, and (b) the target being darker than the background on the other two multispectral records.

Suppose, the spectral bands of Figure 99 are chosen for the multispectral filters as follows:

Record #	Spectral Bands
1	A
2	B+C
3	D
4	E

The following four combinations could be used in the additive color presentation of the scene:

Record #	Viewing Filter	Record #	Viewing Filter
1 4 1	Red Green Green	2 4 1	Magenta Green Deep Yellow
2 2 4	Blue Blue Red	1 3 4	Deep Yellow Deep Yellow Cyan

The graphical analysis for multispectral camera filter selection is by no means accurate as the statistical tests. Hence, some modification of the filters may be required and it is recommended that a preliminary flight test be conducted to assure adequate discrimination between objects in the scene.

7.1.4 Selection of Films for Multispectral Photography

A normal emulsion is inherently very sensitive to low wavelength radiation including x-rays, gamma-rays, ultraviolet light, and the shorter wavelengths in the visible spectrum since it is these radiations which are readily absorbed by silver halide crystals. If an emulsion is to be sensitive to longer wavelength radiation, it is necessary to make the silver halide crystals absorb such light; this is effected by adding dyes to the silver halide grains.

Originally, the addition of dyes increased the halide sensitivity to about 600 nm and the resultant film was called *orthochromatic*. It possessed no sensitivity to deep orange and red light. Further dye research permitted the range of emulsion sensitivity to be extended into the red region (to about 700 nm) and the film was called *panchromatic*. As time progressed, three types of panchromatic films were developed called Types A, B, and C. Figure 100 shows the sensitivity curves of ortho and types B and C pan films. Type A has extremely low green sensitivity; hence, it is not widely used and most pan films today are of the B and C type. Type C has greater red sensitivity which increases the overall speed of the emulsion, while type B closely compares with the sensitivity of the eye. If the eye were viewing colors in relative shades of gray, the sensitivity of the type B pan and the eye would be very similar. Film manufacturers have found that by mixing the dyes in an emulsion, a film can be made sensitive to different spectral regions or the film can be made more sensitive to one color and less sensitive to another. An extended red sensitivity film was developed in 1957 which permitted photography to be taken not only in the visible spectrum, but also in the near infrared.

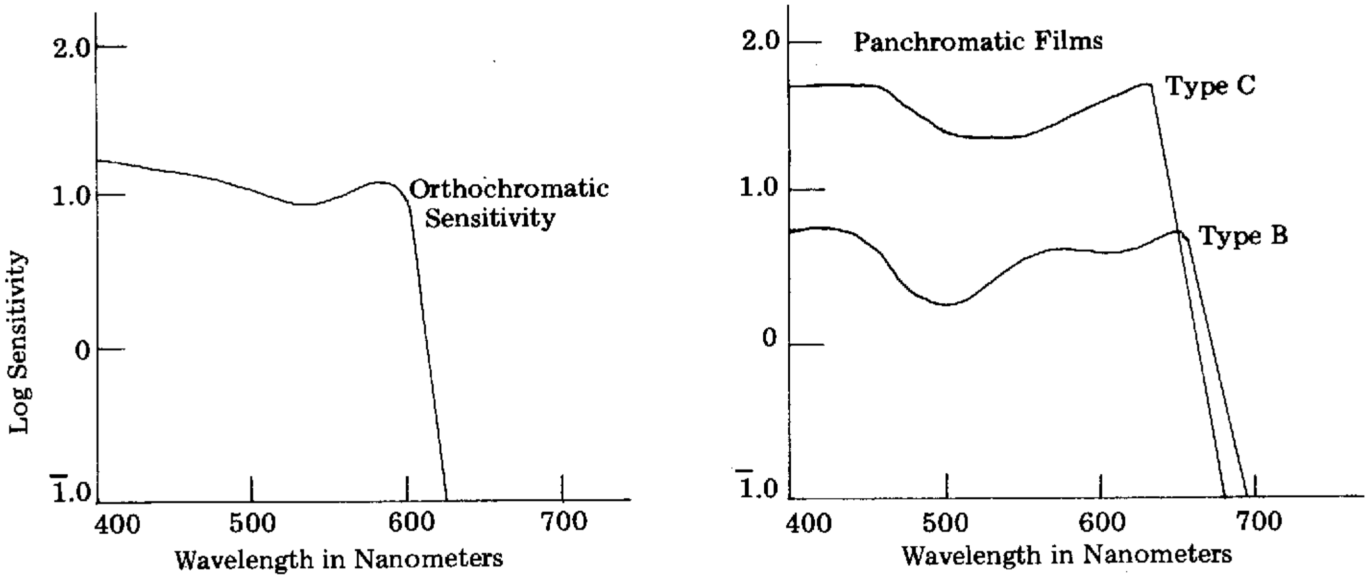


Figure 100. Sensitivity curve for panchromatic and orthochromatic type films.

The silver halide crystals which are embedded in most commercial emulsions range in size between .1 microns and 4 microns in diameter. Fine-grain films will generally have a predominance in the lower end of this range, whereas coarse-grained films will occupy a span in the upper end of the range. The size of the grains in the film are dependent first upon the process used to introduce them into the emulsion. The fine grains occur when the chemicals are quickly dumped into the solution and large grains result when the chemicals are poured slowly into the emulsion.

Silver halide particles embedded in an emulsion are basically single entities. That is, when light strikes the film, the grains are either exposed or not, no grain is half-exposed. Also, *the larger the* *particle, the more sensitive it is to light;* finer particles require more illumination to expose them. Hence, if an emulsion were constructed with only single size grains, the point of adequate exposure would be reached by all particles simultaneously and no gradation of tones would be produced. It is for this reason that emulsions contain a range of silver halide sizes. *If the average size of the grains is large, the emulsion is considered fast,* whereas if the grains are small, the emulsion is slow in speed.

There exists one important trade-off which must be made in selecting an emulsion for multispectral photography. If one requires high resolution in the final image, then a fine grain film should be used. However, the bandwidth of the multispectral filters may be such that inadequate exposure will result from such a choice. Hence, one selects the *finest* grained film which will provide *adequate* minimum exposure in the spectral bands selected. This task amounts to little more than having a film catalog and selecting the highest speed film which is sensitive to the regions covered by the multispectral filters. For example, consider a case of photographing objects submerged in water. The film selected must have adequate speed for the scene being imaged, i.e., not land but sub-surface objects. Conversely, when taking aerial imagery over desert test sites, one can employ a rather fine grained slow film because the terrain reflectance is so high. Regardless of the scene, it is absolutely necessary to select and expose the film based upon the objects of interest and not the general terrain. Much of multispectral photography is rendered useless because of this oversight.

7.1.5 Exposure Calculations

The illumination which is reflected from the scene in the form of brightness is modified not only by the lens and filter transmission, but by the lens aperture as well. The final exposure which forms the image is a function of the reflected light from the terrain (B), the transmission of the lens (T_L), the filter (T_F), the f/number of the lens (f), and the shutter speed (t). Consider, for a moment, the variables entering into the final equation for photographic exposure:

- B: Brightness is actually equal to the incident illumination times the object's reflectance (this is the value given by the reflectance radiometer). The solar illumination at the time of flight will be fixed as will the target reflectance; hence, B is *not variable.*
- T_F: The filter transmission is fixed by its manufacturing process and so is also *not available.*
- TL: Similarly, the lens transmission is *not variable.*
- f: Most lenses provide for a selection of f/numbers so that f *is varaible.*
- t: Although most lenses provide for some control of the exposure time, each multispectral shutter should be set at the same value. This assures that any aircraft motion which might be recorded by the camera (in terms of image displacement) will be the same for each multispectral record.

In short, the one variable left open with which to create the correct photographic exposure is the f/number. Although some lenses have a rather limited range of f/stops, it is imperative that the smallest f/number be as low as possible. One can always add neutral density filters to further reduce the light entering the camera, but the opposite is not true. Consider Table XIII.

f/number	Equivalent (f/number — ND Combination)
1.4	f/1.4
2.5	f/1.4 + .3 ND
4	f/1.4 + .6 ND
5.6	f/1.4 + .9 ND
8	f/1.4 + 1.2 ND
16	f/1.4 + 1.5 ND
22	f/1.4 + 1.8 ND
32	f/1.4 + 2.1 ND

Table XIII

As far as exposure is concerned, a lens could have a fixed aperture of low f/number, the higher f/numbers being simulated by the choice of neutral density filters. Note: Some neutral density filters are not neutral in the near-infrared part of the spectrum (e.g., Eastman Kodak Wratten #96 series) and care should be taken that use of such filters is avoided when photographing between 700 and 900 nm.

The equation used to determine the proper f/number for each spectral band will now be derived. Referring to Figure 101, let s^2 be the area of the image, S^2 the area of the object, F the focal length of the imaging lens, and L the lens-to-object distance. Then, when S is infinitely far from the lens:

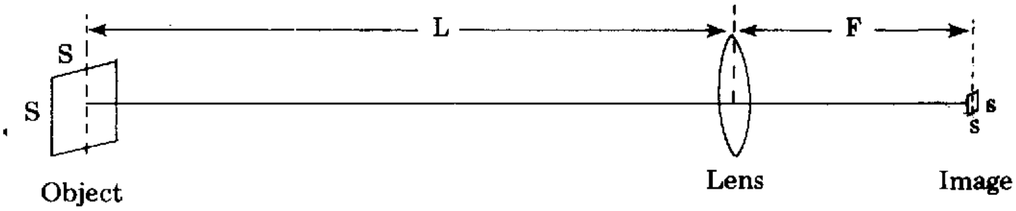


Figure 101. Illumination at the image plane of an infinitely distant object.

$$s^2 = S^2 \left(\frac{F^2}{L^2}\right) \text{ in } (\text{cm}^2)$$

Now, let I′ be the solar illuminance falling onto the object in the scene and ρ the inherent reflectance of the object. The reflected brightness B is then:

$$B = I'(\rho) \text{ in microwatts/cm}^2$$

The illumination at the front of the lens is $I = B \frac{S^2}{L^2}$ in $\frac{\text{microwatts}}{\text{cm}^2}$

The area of the lens aperture is given as: $\frac{\pi D^2}{4}$

Hence, the total light energy through the lens aperture is: $\frac{BS^2}{L^2} \quad \frac{\pi D^2}{4}$ in microwatts

The illumination I per unit area, s^2, therefore is: $I = \frac{BS^2}{L^2} \cdot \frac{\pi D^2}{4} \left[\frac{L^2}{S^2F^2}\right] = \frac{\pi BD^2}{4F^2}$ in $\frac{\mu \text{ watts}}{\text{cm}^2}$

or $I = \frac{\pi B}{4f^2}$ in $\frac{\mu \text{ watts}}{\text{cm}^2}$

The photographic exposure accounting for lens and filter transmission is defined as:

or: $E = I(t) = \frac{\pi B}{4f^2} \cdot T_L \cdot T_F(t)$ in $\frac{\mu \text{ watts} \cdot \text{sec}}{\text{cm}^2}$

$$E = \frac{B}{4f^2} \cdot 10 \cdot T_L \cdot T_F(t) \text{ in } \frac{\text{ergs}}{\text{cm}^2} \qquad \text{Equation7-1}$$

This equation represents the photographic exposure for any multispectral record. Suppose, now, that we have decided that the minimum exposure which a multispectral record should get is one that will produce a density on the film of .3 above base plus fog. Film manufacturers supply curves for their emulsions which indicate the exposure required to produce a certain density. These are called sensitivity curves, an example of which is shown in Figure 102.

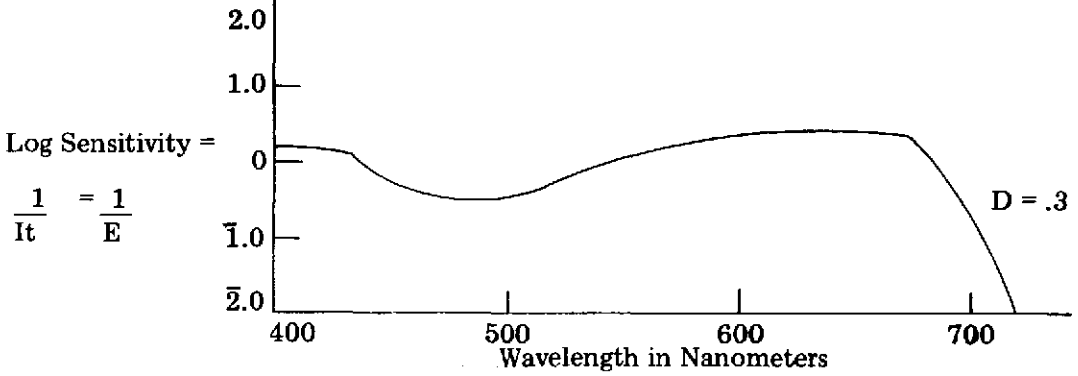


Figure 102. Example of spectral sensitivity of film or exposure required to produce a density of .3 on the film.

The bandwidth of the filter under consideration is drawn on the sensitivity curve as shown in Figure 103 and the average sensitivity for the filter band is determined. Film sensitivity is defined as:

$$\log S = \log \left(\frac{1}{E}\right) \text{ or } E = \frac{1}{S} \text{ in } \left(\frac{\text{cm}^2}{\text{ergs}}\right)$$

From this relationship, the minimum exposure for the filter band is obtained and substituted into equation 7-2:

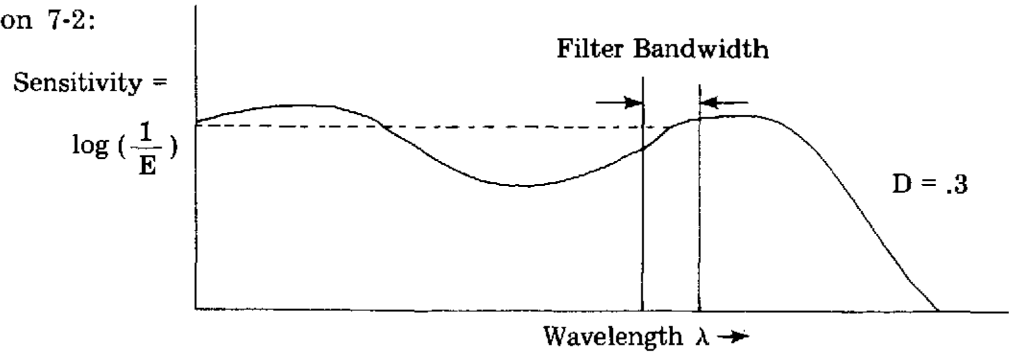


Figure 103. Sensitivity of film to a particular filter bandwidth.

$$f^2 = \frac{B}{4E} \cdot 10 \cdot T_L \cdot T_F(t) \qquad \text{Equation 7-2}$$

Each of the variables in equation 7-2 are fixed prior to flight with the exception of the reflected scene brightness B and the f/number. The brightness is measured at flight time using either a photometer equipped with the spectral filter or the spectroradiometer. Substituting B into equation 7-2, yields the correct f/number required to produce the predetermined minimum density.

It should also be noted that optimal exposure of a scene is such that after development, the objects of interest lie on the straight line portion of the characteristic curve. By way of illustration, consider a strip of film exposed through a multispectral filter, F, with two objects of interest, M and N, being imaged. A sensitometric step wedge is exposed on one end of the film through the same multispectral filter. The resultant H and D curve after processing is shown in Figure 104, curve #1, where A_1, B_1 represents the straight line portion. Objects M and N possess densities D_1 and D_1' respectively; object N lies on the straight line curve #1, whereas object M falls along the toe. Assuming that the shape or gamma (γ) of the curve is satisfactory, one may determine the correct camera exposure necessary to place both M and N between the points A_1 and B_1 on the curve; this is done in the following way:

1. Redraw curve #1 on a piece of tracing paper indicating the points A_1 and B_1.
2. Slide the traced curve from right to left so that an extension of the vertical lines M and N will intersect this second curve along the straight line (A_1, B_1). The extended lines M and N are shown in Figure 104, the traced H and D curve being designated as #2.
3. Read the new values of density D_2 and D_2' from the y-axis.
4. $\gamma = \dfrac{\Delta D}{\Delta \log \text{exposure}}$ (along the straight line)

hence,

$$\left(\frac{D_2' - D_1'}{\gamma}\right) = \Delta \log E$$

or

$$\log\,[D_2' - D_1'] - \log \gamma = \Delta E$$

where ΔE is the increase in exposure required.

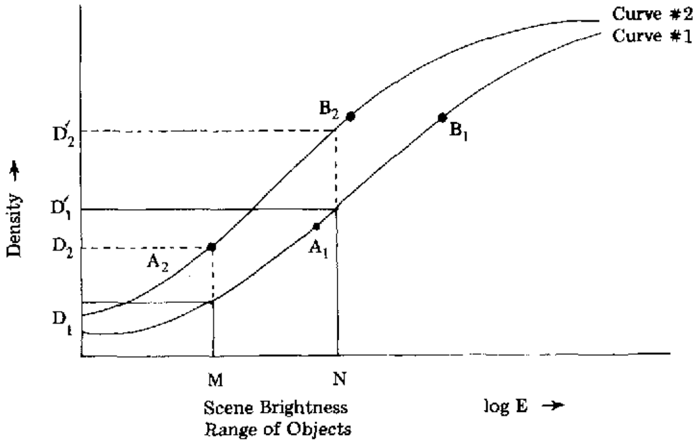


Figure 104. Exposure correction necessary when objects of interest do not fall on straight line portion of H and D curve.

5. Point N corresponds to log E_N of one of the original images; take the logarithm of E_N.

6. $$\frac{E_N + \Delta E}{E_N} = T$$

where T is the number of times the original exposure, E_N, required to place both objects on the straight line of the characteristic curve. Example: Suppose E_N is 160 and $\Delta E = 160$. Then,

$$\frac{160 + 160}{160} = 2 = T$$

This means that the new exposure must be two times or twice the original exposure of 160. Suppose: E_N is 160 and $\Delta E = 20$. Then,

$$\frac{160 + 20}{160} = \frac{180}{160} = 1.12 = T$$

This means that the new exposure must be 1.12 times the original. The same analysis applies to shifting the traced curve in the other direction to reduce the exposure.

It should be noted that the requirement for all objects to lie on the straight line portion of the H and D curve is not always possible:

— Sometimes the sensitivity of the film in isolated spectral regions is not sufficient to produce densities corresponding to the straight line area. As an example, EK infra-red, black-and-white film #2424 has a low sensitivity in the green region. Exposing the film with the green lens wide open sometimes yields inadequate exposure. This is one of the principal reasons for taking multispectral imagery on clear, bright days when the sun angle is high. In spite of all precautions, the optimal exposure for each band is sometimes a compromise; that is, placing the objects of interest as close to the straight line as possible.

7.2 Processing Control for Multispectral Imagery

Chapter 5 discussed general darkroom sensitometric techniques, as well as the basic processing requirements of temperature control, chemical strength, development time, etc. Under the conditions of precision processing, the fundamentals of developing, fixing, washing, and drying remain the same except that the procedures are improved and controlled by exacting methods. The goal of precision processing, then, consists of performing the laboratory procedures to pre-established standards of accuracy which will produce an optimal set of results for the photographic material used. This goal requires that the development process be both accurate and precise. Whereas precision relates to the exactness of the process and the variations within it, accuracy is thought of in terms of the finished product; that is, the correctness of the final resultant image. All results are checked with instrumentation so that consistent repeatability is obtained.

A precision photo lab will consist of a large area divided into separate rooms in order to isolate the various functions for efficiency and cleanliness. Although the extent and size of the laboratory equipment will depend on the expected photo accuracy, as well as the amount of processing per day, the function of each instrument (sensitometer, densitometer, colorimeter) must be checked and calibrated at regular intervals. In addition to equipment performance, the film and processing conditions (chemical mixture, gamma, speed) must always fall within pre-defined limits to assure consistent multispectral results. A graphical method of displaying the performance of both the dark room instrumentation and the development process can be facilitated with the use of control charts.

Control charts for any process give a pictorial idea of past performance and allow one to detect trends and observe when the process is out of control. Variations beyond the pre-defined limits can seriously affect the photo product if left unattended. The series of control charts also indicate whether or not corrective action should be taken in order to bring the process back into tolerance. In order to construct control charts for the processing and measurement of multispectral imagery, some preliminary study of variation is required. Variations exist in every instrument and in every process. The nature of the variation must be determined, as well as its tolerable limits before any actual variation can be compared to that which is allowed.

Most development processes follow what is known as a normal distribution. Normal distributions arise from the operation of chance; that is, when chance factors exist and the effects of these factors are about equal in their influence upon the process, a normal pattern arises. When other than a normal distribution occurs, we assign to it a cause other than chance. Two numbers describe the characteristics of normality: the average or arithmetic mean (μ) and the distance from the mean to the point of inflection on the curve called standard deviation (σ).

The mean or sample average not only identifies the maximum point of the distribution, but it also indicates the average value of the variable. The significance of the standard deviation is readily understood as: between the point $\pm 1\sigma$ lies about 68% of the data; between $\pm 2\sigma$ 95% of the data falls, and between $\pm 3\sigma$, exists about 99% of all the data, while the remaining 1% lies somewhere outside. The arithmetic mean and standard deviation can be illustrated with the following example: There exists a photographic process in which the average gamma is 2.0 having a standard deviation of .1. This means that 68% of all the tested gammas were between the limits of 1.9 and 2.1, 95% of the gammas were between 1.8 and 2.2, while 99.7% were between 1.7 and 2.3; the remaining .3% of the H and D curves had gammas less than 1.7 or greater than 2.3. If the process yielded a gamma of 2.2, we would say that the process was under control. A gamma of 1.2, however, would indicate an unusual set of conditions and the process would have to be corrected. Assessment of the process deviation is the primary purpose of the control charts. The following mathematical equations define the mean and the standard deviation of a normal distribution.

Mean: $$\bar{X} = \frac{(X_1 + X_2 + X_3 + \ldots + X_n)}{n}$$

Where: $X_1, X_2, X_3, \ldots, X$ are the values of the variable — gamma, film speed, etc.
$\bar{X}$ is the mean of the variable values
n is the total number of values or sample readings.

Standard Deviation: $$s = \sqrt{\frac{n\,\Sigma(X^2) - (\Sigma X)^2}{n(n-1)}}$$

where n, X are the same as above and s is the standard deviation. The procedure for calculation of $\bar{X}$ and s is given in Table XIV. A simplified control chart for any instrumentation or processing performance can be prepared in the following way:

1. Determine the variables to be controlled for Example,
   - Densitometer stability — high and low readings.
   - Chemistry stability — pH, developer concentration in (grams/liter), solution temperature, machine running speed, etc.

   - Processing stability — gamma, ASA speed.
   - Printer optics performance — resolution, exposure.

2. Make preliminary tests for 15 consecutive days measuring the variable at least four times during each day.
3. For each day, average the readings.
4. At the end of fifteen days, compute the mean and the standard deviation.
5. On a piece of linear graph paper mark off the x-axis by days. The central y-axis is set at the mean value of the variable, while the upper and lower limits are the 1o, 20, and 3o values as shown below in Figure 105.

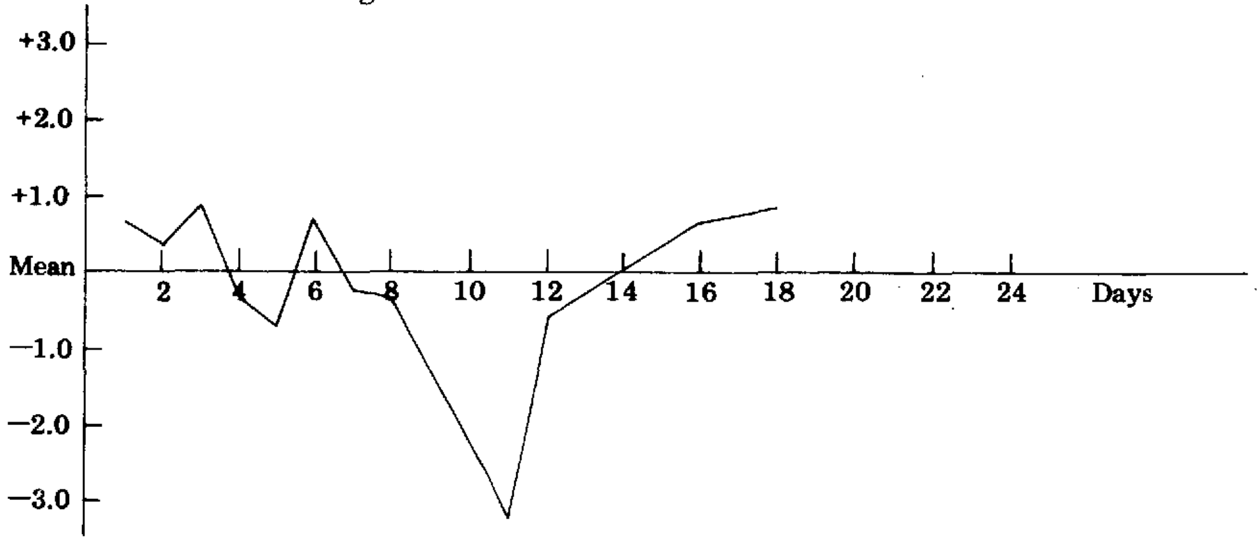


Figure 105. Example of control chart for processing of multispectral imagery. Note that the process is out of control on the 11th day.

Each day the data is measured and plotted on such a control chart. When the point extends beyond the predetermined limit, the process is unstable and corrective action must be taken. Sometimes a single data point will fall outside the control limits. Usually it will be noticed that in the four measurements per day, one is abnormal. Providing the others are not equally as bad, that particular point may be dropped. Control charts such as that shown in Figure 105 are constructed for as many variables as possible in order to obtain repeatable processing results, a condition which is essential in multispectral photography.

Besides maintaining control of the processing so that optimal negatives always result, there is one major consideration for the development of multispectral imagery. The negative gamma must be as high as possible without placing any of the objects of interest on either the toe or shoulder of the characteristic curve. The higher the gamma, the smaller will be the log E range. In addition to the scene brightness range, the only major limitations on gamma are the inherent characteristics of the film and the development chemistry. The primary rule is to adequately test the entire development process before risking a valuable and, perhaps, irreplaceable roll of film to an unstable process.

7.3 Negative Film Desnitometry

The primary purpose of the use of sensitometric wedges in the processing of multispectral photography is one of quality control. Both the speed of the emulsion and the gamma (contrast) of the negative image are affected by the developer used and the degree of development given. Therefore, if the exposure given each spectral band is established by data collected in a previous exposure test, it is essential that the final imagery be given the same processing as the test. The procedure is as follows:

Control Variable: ____________________ Process I.D.: ________________

Date: ____________________ By: ________________

Sample Number	Variable Values (X)	(X^2)	Computation
1			$n = (\qquad)$
2			$(n\text{-}1) = (\qquad)$
3			$n(n\text{-}1) = (\qquad)$
4			
5			$(n)\ \Sigma\ (x)^2 = (\qquad)$
6			
7			$\sqrt{\dfrac{n\ \Sigma\ (X)^2 - (\Sigma X^2)}{n(n\text{-}1)}} =$
8			
9			$s = (\qquad)$
10			
	$\Sigma X = (\qquad)$	$\Sigma(X^2) = (\qquad)$	$\dfrac{\Sigma(X)}{n} = (\qquad) = \overline{X}$
	$\Sigma(X)^2 = (\qquad)$		
	Add up column and then square	Add up column	

Max. X = ________________ , Min. X = ______________

R* = (Maximum ________) — (______ Minimum) = ( )

*R is the range or difference between the highest and the lowest value of X

Table XIV

1. A sensitometric wedge is exposed on the test film and processed with the test imagery. The exposing source should be of daylight quality and should not be spectrally filtered.
2. The densities of the processed wedge are measured on a densitometer and the characteristic curve plotted. For this purpose the densities of each step of the original wedge (used for exposing) are recorded on the absicissa (horizontal axis) of the graph paper. The density increments are usually about 0.15. These densities serve as the relative log exposure values. The density of the corresponding step of the reproduced wedge is plotted on the ordinate (vertical axis). A typical characteristic curve is shown in Figure 106.
3. Before the final imagery is processed, a wedge is exposed on a small piece of the same emulsion as was used for the final imagery. This is then processed under the same conditions as the final test. The results are measured and plotted and the curve compared to the curve of the first test. Adjustments in development time should be made to correct for any differences in speed or gamma of the two curves. Differences may occur due to differences in the emulsion batches, deterioration during storage, or changes in the chemistry of the developer.
4. A wedge should be exposed on the leading and trailing ends of each roll of imagery processed, as a check on consistency of development through the length of the roll.

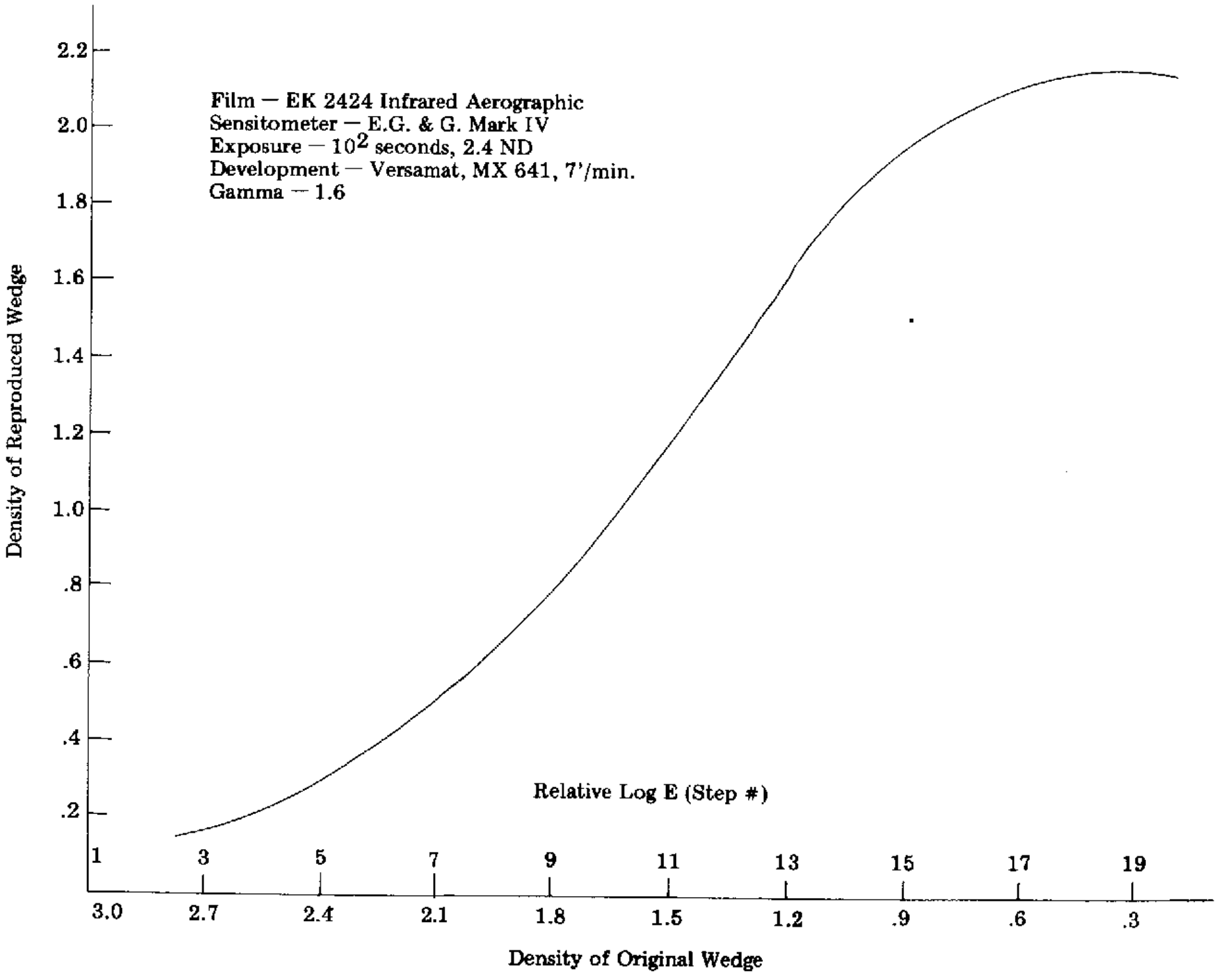


Figure 106

Sensitometric wedges are also useful in matching gammas of the spectral images. The gamma of the developed image varies with the wavelength of the exposing energy, as well as with development time. Therefore, if each spectral image is recorded on a separate roll of film, the development of each may be adjusted to provide equal gamma on each. In order to do this, each film must be exposed with the camera filter placed in the sensitometer, in addition to any filters required to achieve daylight quality. Some adjustment of the intensity of illumination may be required in order to achieve a full range of densities in the negative wedge. When all spectral wedges have been read and plotted, the gammas may be compared. Time-gamma curves, published by the film manufacturer, may be consulted for information on approximate new development times. Exact matching of gammas will require further tests.

The spectral sensitometric wedge may also be used in subsequent analysis of the multispectral negative imagery. If the densities of areas of interest in the multispectral imagery are measured, their positions on the H & D curve can be easily located. Their separation on the relative log exposure axis (the abscissa) can then be converted to relative brightness differences in that spectral region. This is illustrated in Figure 107. Here, the negative density of area A was measured and found to be 1.55 and area B to be 1.15. When plotted on a sensitometric curve exposed through the same spectral filter, their separation on the relative log E axis was .30. Since the abscissa is a log, this indicates a factor of 2. Area A was approximately twice as bright as area B in this spectral region. If the reflectance characteristics of one are known, the other can be calculated. If area A is a calibrated target panel placed in the scene, for example a neutral gray reflecting 64% of the energy incident upon it, then area B reflects approximately 32% of incident energy in this spectral region. These figures are only approximate as this simplified method does not take into account certain factors that also affect image density, such as atmospheric scattering, lens flare, and vignetting.

When the spectral wedges are printed along with the imagery to produce a transparency for additive projection, the positive wedges may be read and plotted to provide a simplified method of calculating system gammas of each spectral region. System gamma is the gamma of the complete negative-positive process as opposed to process gamma which is the gamma of a single step of the process.

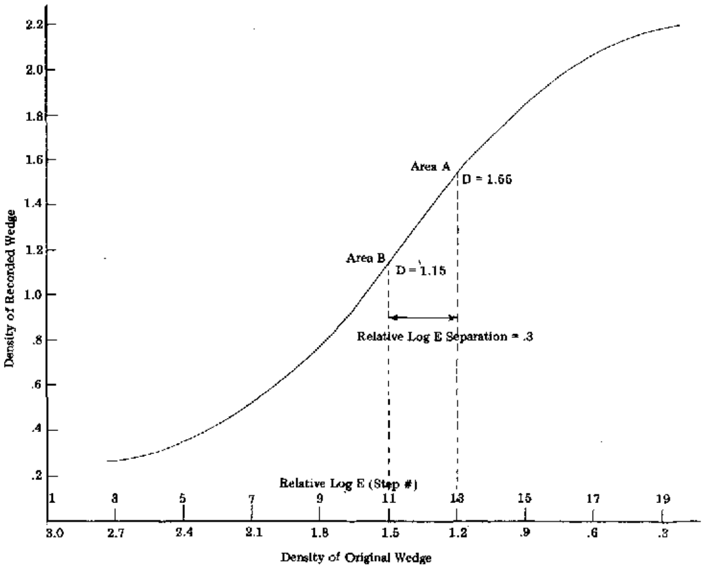


Figure 107. The use of spectral sensitometric wedges in sensitometric analysis of multispectral imagery.

7.4 Summary

- In situ spectral measurements are essential to the correct selection of multispectral camera filters.
- Perceived spectra of a target does not account for the quality of the illuminating radiation.
- Inherent spectral removes the biasing effect of the illuminant from the reflectance measurements.
- Filter selection is made using inherent spectra.
- Four sets of reflectance measurements (each set containing four scans) is the minimum number required for spectral analysis.
- As the bandwidth of the spectroradiometer decreased, the reflectance distribution for the object becomes more accurate.
- Statistical analysis of spectra should consist of at least one parametric (t) test and one non-parametric (Mann-Whitney) test.
- t-test assumes that the spectra follow a normal distribution pattern.
- Mann-Whitney test makes no assumptions regarding the distribution of the spectra.
- A simple graphical analysis of the spectra can be performed, although it is not nearly as accurate as the statistical test.
- The film selected for multispectral photography should be the finest grained emulsion which will provide adequate exposure of the scene.
- Multispectral camera exposure is controlled by the f/stop selected which, in turn, is related to the scene brightness at the time of flight.
- Objects of interest on multispectral negative imagery should fall on the straight line portion of the characteristic curve.
- Control charts should be generated for the development process, as well as the dark room instrumentation in order to assure accurate and repeatable multispectral results.
- Multispectral negative gamma should be as large as possibel without placing objects of interest on either the toe or shoulder of the H and D curve.

CHAPTER 8

POSITIVE DUPLICATION OF BLACK-AND-WHITE MULTISPECTRAL NEGATIVES

The previous chapters discussed the conditions for the correct exposure and processing of multispectral negatives including:

- —— calculation of correct exposure and the need for identical shutter speeds to avoid reciprocity failure effects,
- —— need to place subjects of interest on the straight portion of the characteristic curve,
- —— selection of films as a function of subject brightness, film speed, and grain,
- —— selection of gamma consistent with the scene brightness range.

Once these conditions have been fulfilled, a set of good multispectral negatives are available for printing. Negative multispectral imagery is generally unsuitable for additive color viewing because of the inversion of the brightness scale (highlights look like shadows and vice-versa) and because there still exist differences in contrast and gamma between the multispectral records. To correct these shortcomings the negative images are reproduced or duplicated onto a suitable transparent material. The exact choice of a duplicating film will vary according to the desired result, but most materials fall into one of two classes: normal and high definition. Unless extremely fine resolution is required, a normal definition film, such as Kodak Type 2420, is acceptable. Of all the duplicating materials, this type is capable of the highest gamma.

Whatever emulsion is selected for the duplication of multispectral records, it must possess certain characteristics:

- — a clear base to minimize transmission losses through it during projection,
- — a stable base to minimize the dimensional changes during processing and storage,
- — adequate range of gamma controllable through processing,
- — a non-panchromatic sensitivity (preferably only blue sensitive) to enable handling under safelights during processing,
- — a speed which is compatible with the printer illumination system. Slow speed films exposed in a low illumination printer require extremely long exposures, while fast speed films in high illumination printers require extremely short exposure. Both of these exposure conditions are difficult to control accurately and repeatable results (in terms of density) are not always possible.

8.1 Multispectral Positive Printing

Multispectral negatives may be duplicated either by projection or contact printing. The primary advantage of projection printing lies in the fact that it is possible to make small correction in the scale of the multispectral records. Such correction is necessary if: (1) the camera lenses were not matched for differential focal length (see chapter 10), and (2) if there exists no provision for scale correction in the additive color viewing system. The lens used for projection printing must give excellent definition on a *flat* surface for the range of enlargement or reduction necessary. Also, since the image is visually focused, the projection lens must be well corrected for both lateral and logitudinal chromatic aberration. The position of the negatives in the object plane of the projector is also critical because of the inherent distortion of the lens. For example, if one multispectral record is displaced in the object plane relative to the positions of the other three, then the distortion of any image in the displaced record will differ from the distortion of the same images in the other records. Such a situation will give rise to registration errors in the additive color viewer.

A rather simple procedure can be employed to assure both accurate scale correction in the transparencies and correct positioning of the negatives in the projector object plane.

1. Place one of the negative records in the projector object plane.
2. Make a positive print of this record using an extremely fine grain *paper.*
3. After processing and drying, center the print in the image plane of the projector. Care must be taken that the print is held flat. This can be done by dry mounting the print onto a heavy, smooth cardboard surface and tipping this to the easel.
4. Place one of the negative records in the object plane of the projector and register it to the positive print, both in scale and in x, y position.
5. Place the duplicating film material over the reference print and expose.
6. Remove this negative record and repeat steps 4 and 5 for the remaining three multispectral records.

Negatives duplicated in a contact printer may be illuminated by either parallel or diffuse light. Parallel light is commonly used when negatives of good quality are to be reproduced. The source of illumination is, generally, a small point source placed at a large distance from the film plane. With the emulsion of the duplicating material against the emulsion of the negative, the greatest image definition is obtained with parallel light as shown in Figure 108. If, however, the negative is illuminated with non-parallel light, some flaring of the duplicated image takes place as shown in Figure 109. The resultant effect of using diffused illumination is a decrease in resolution, although the contrast is increased owing to the path length of the light through the emulsion. Since diffuse light is incident upon the negative at all angles, any scratches on the negative will be lost in the reproduction. Conversely, scratches will be exactly reproduced by using a contact printer illuminated by parallel light.

Resolution losses can also occur in the diffused light printer due to an imperfect contact between the negative and duplicating material emulsions. If both films are held fixed in a vacuum frame, this cause may be attributed to either: (a) insufficient vacuum, or (b) lack of parallelism of the pressure glass or the backing plate. A fairly good indication of emulsion contact can be assured if one sees Newton rings surrounding the area of the photo. No Newton rings should be visible over the surface of the negative, however. The loss in resolution as a result of poor contact between the negative and print material, can be seen in Table XV. The films were diffusely illuminated by a ground glass about four inches below the negative and the two emulsions were separated using shims.

Positive-Negative Material Separation	Resolution
Original negative	21 lines/mm
Good contact between negative and print material	19 lines/mm
.0015" separation between films	11 lines/mm
.003" separation between films	6 lines/mm
.0045" separation between films	4 lines/mm

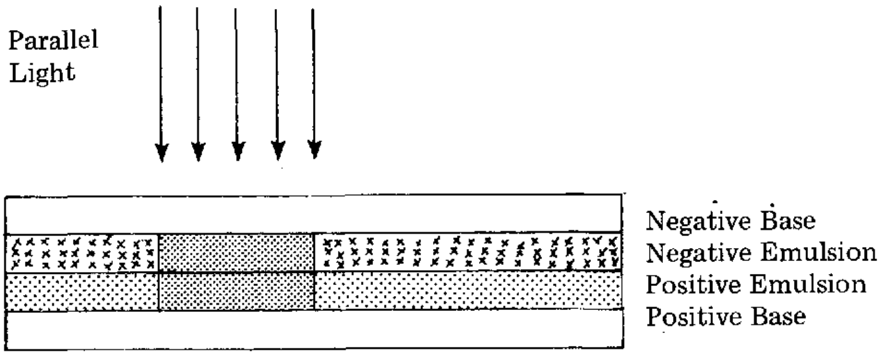


Figure 108. Parallel light source gives greatest image definition in contact printer.

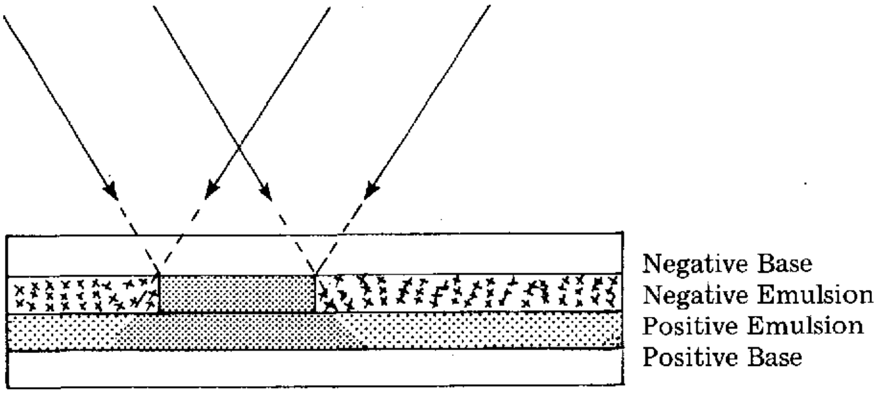


Figure 109. Non-parallel light source reduces flaring around edges of duplicated image in contact printer.

8.2 Characteristics of Multispectral Positive Transparencies

A correctly exposed and processed multispectral positive should have the following preferred characteristics:

- A low base plus fog and low minimum image density.
  These conditions assure that the composite additive color image will have the highest possible brightness. This is analogous to generating the largest chromaticity diagram by taking an orthogonal slice through the color solid at a brightness level of 10. Base and fog density level should be no greater than 0.05 which is generally attainable with EK type 2420 film.
- Identical gammas on each multispectral record if the reflectance of the objects of interest are approximately the same in each filter band. This condition permits the correct balance of the additive color composite image on the multispectral viewer screen. By way of illustration, consider the case when the characteristic curves for two positive multispectral records (red and green) are *not* the same, as shown in Figure 110. If the target color is yellow, then equal amounts of red and green should be projected onto the viewing screen regardless of whether the subject is in the highlight or shadow. An examination of Figure 110 shows that in the

shadow areas between the log E_1 and log E_2 values, this condition holds. That is, the positive transparencies will transmit equal amounts of red and green light since the image densities are identical. However, consider the color produced on the screen when the target is in highlight, log E_3. The green image is less dense (D_3) than the red (D_4) and so will transmit more green light. The additive color of the target will then shift from a yellow towards pea green and could be misinterpreted as some other object. If, however, the gamma of the two records are identical throughout the range of log E, then equal densities will result

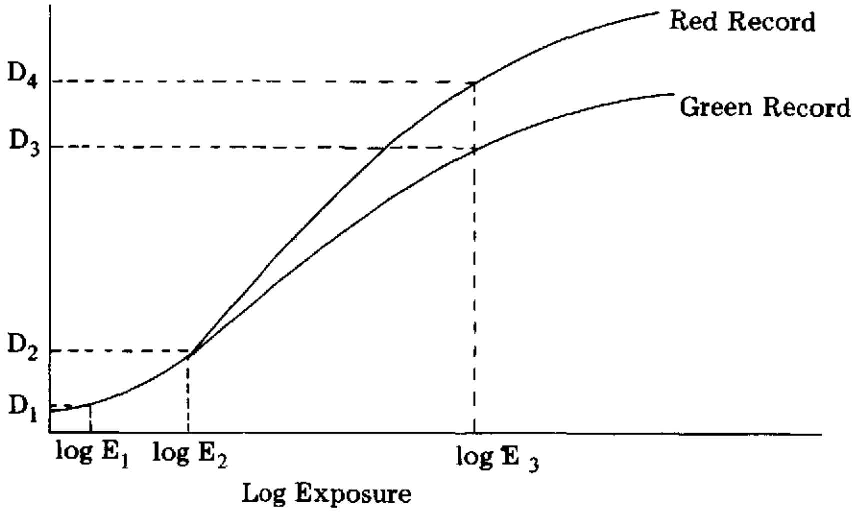


Figure 110. Effect of different gammas upon the additive color reproduction of highlights.

regardless of target brightness. Note: In practice, the curves never quite match throughout the entire scene brightness range. It is desirable, though, that the curves match in the lower part of the H and D curve, i.e., from the point defined as Dmin to the upper density limit for the targets of interest, for example soil and trees. Figure 111 shows the case in which the curves do not match over the entire log E range of the film. They do match, however, over the scene brightness range defined by the subjects. Although it would be most desirable for all targets to be on the straight line portion of the *positive H & D* curve, it is more important that the minimum density be held low for purposes of high viewing brightness.

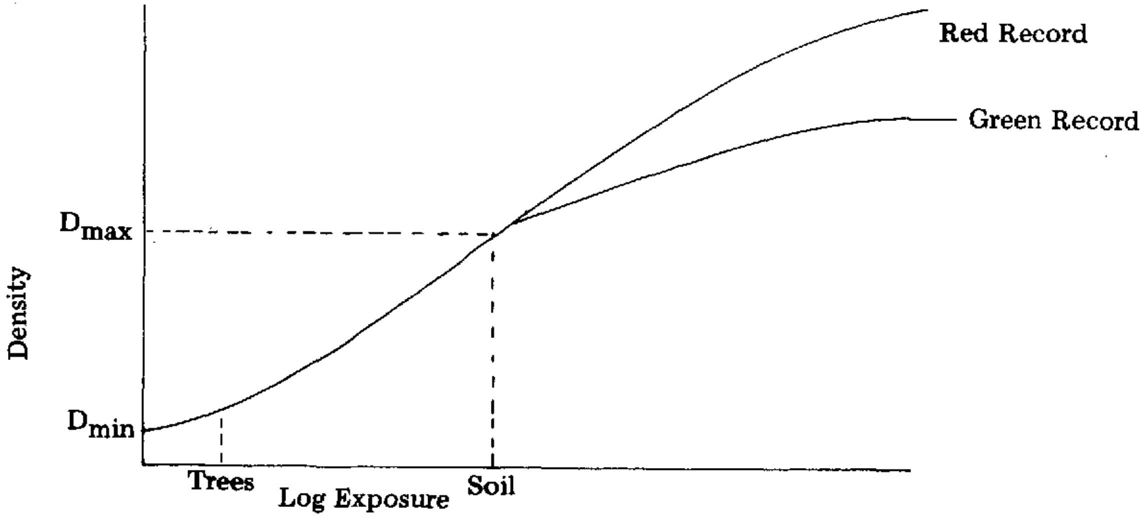


Figure 111. Gamma should match within the scene brightness range when the reflectance of the subjects is about the same in each spectral band.

– When the reflectance or brightness of the subjects in the scene are not the same in each filter band, then the condition of matching the gamma for all records is replaced by a new criteria. The Dmin and the density range of each record must mach. To illustrate this condition, consider photographing both water and soil using an infrared filter and a green filter. The brightness of the soil is about the same in both filter bands, whereas the brightness of the water is high in the green and very low in the infrared. Let Figure 112 be the H & D curve for the infrared positive transparency and Figure 113 be the curve for the green positive transparency. Notice that the gammas are the same and the Dmin's (soil) are matched. There is little density difference between the soil and water in the green record. In order to enhance the color differences in the green region, the positive is processed to a higher gamma,, while maintaining the same Dmin as shown in Figure 114. Now the density difference between the land and water on the green photo is the same as that of the infrared and good additive color discrimination will result.

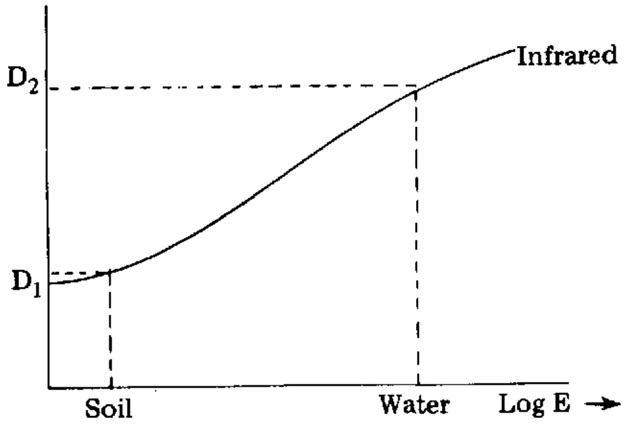


Figure 112. Scene brightness range of soil and water on the positive infrared multispectral record.

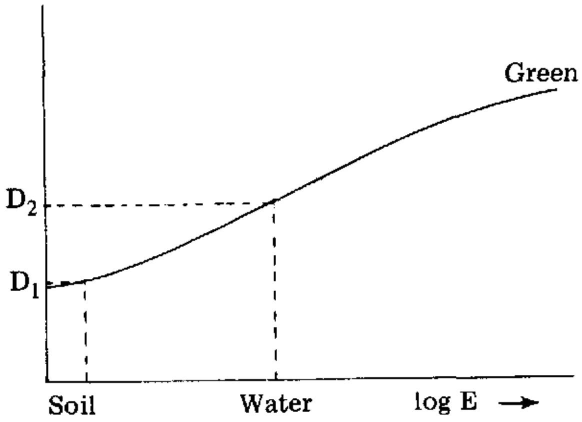


Figure 113. Scene brightness range of soil and water on the positive green multispectral record.

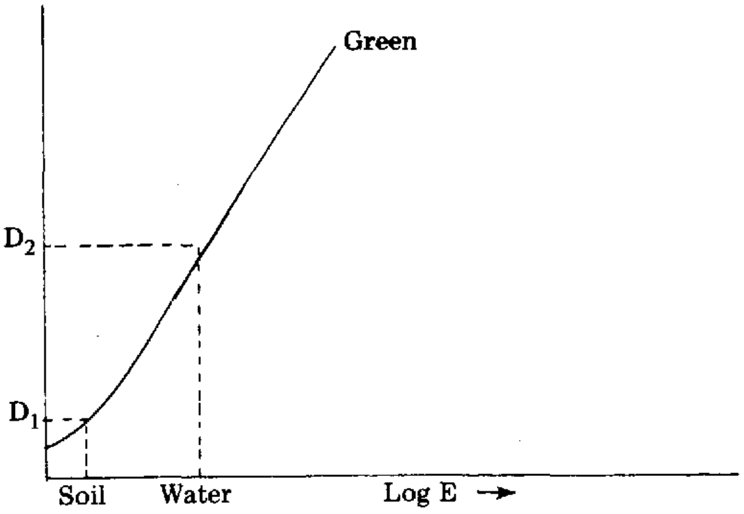


Figure 114. Expansion of density range by increasing the gamma of the green record.

Summarizing the requirements for each multispectral record:

- Negatives are exposed so that objects of interest fall on straight line portion of characteristic curve.
- Negatives are processed to the highest possible gamma which the film can produce without placing any objects of interest on toe or shoulder. Figure 115 shows a series of characteristic curves for the same emulsion type. Although curve D has the highest gamma, the highlights fall on the shoulder so that curve C is the optimal choice.
- Select duplicating material which is blue sensitive, has stable base, and will yield the greatest possible gamma.
- Exposure duplicate film so that brightest target of interest has lowest possible density (Dmin).
- When the scene brightness range is approximately equal on all records, process the duplicating film to the same gamma if possible.
- When the scene brightness range differs in each multispectral record, the duplicating material is processed to different gammas such that the density range of each record is equal.
- Same precision processing conditions must exist for the positives, as well as the negatives.

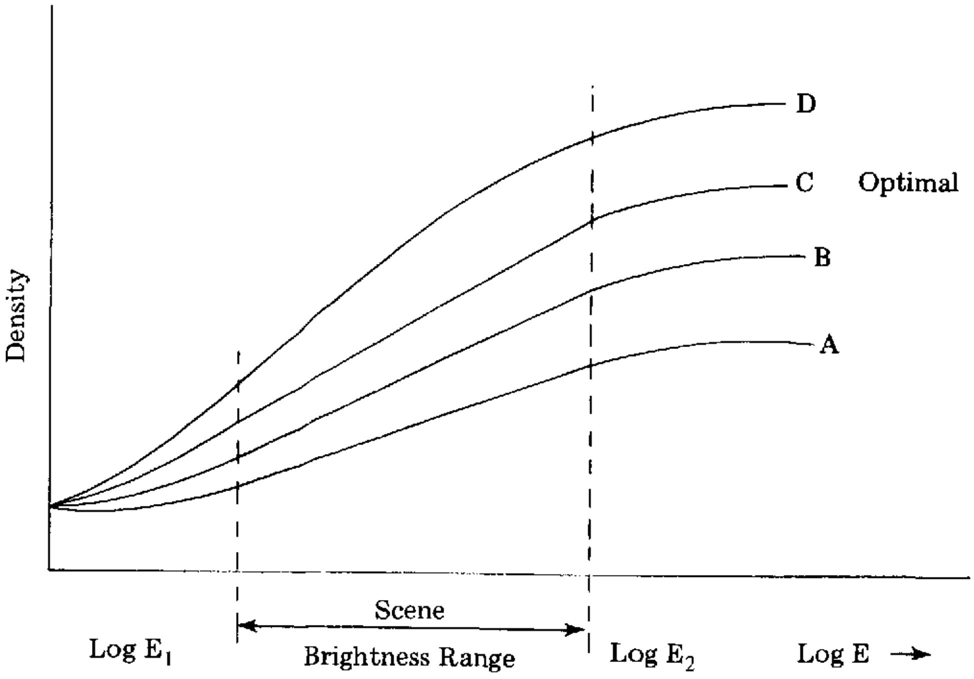
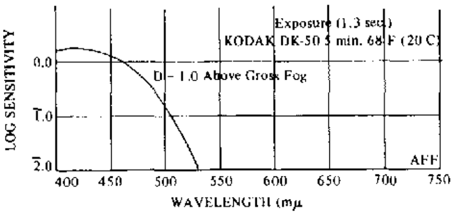
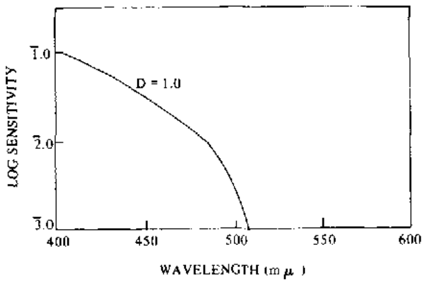


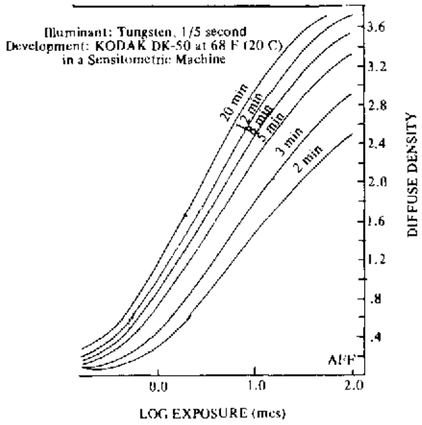
Figure 115. Optimal gamma is highest possible value still producing scene brightness range on straight line.



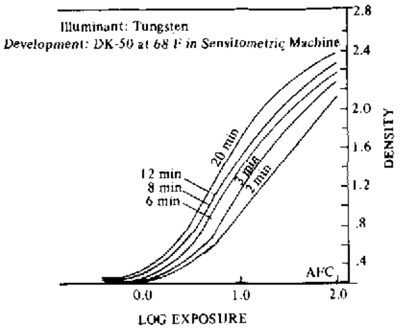
Curve A



Curve B



Curve C



Curve D

8.3 Characteristics of Duplicating Materials

	Kodak Aero Dup #2420	Kodak Aero Dup #4427	Kodak Aero Dup #2430
Base	Estar	Estar	Estar
Base Thickness	4.0 mil	7.0 mil	4.0 mil
Backing	Fast Drying (PX)	Clear Gelatin	Fast Drying (PX)
Design Goal	Max. Dimensional Stability	Max. Dimensional Stability	For High Acutance Negatives
Safelight	Kodak #1A	Kodak #1A	Kodak #1A
Sensitivity	Blue	Blue	Blue
RMS Granularity	16 (in DK-50 developer for 5 min. at 68•F and read at net density = 1.0)	16 (in DK-50 developer for 5 min. at 68•F and read at net density = 1.0)	8.9 (in DK-50 developer for 4 min. at 68•F and read at net density = 1.0)
Resolution	138 l/mm at 1000:1 84 l/mm at 1.6:1	138 l/mm at 1000:1 84 l/mm at 1.6:1	285 l/mm at 1000:1 120 l/mm at 1.6:1
Spectral Sensitivity	Curve A*	Curve A*	Curve B*
Sensitometric Curves	Curve C*	Curve C*	Curve D*

*See following page

8.4 Reproduction of Tone

The technical aspect of photographic quality deals with the manner in which the image densities relate to the reflectance or brightness of the scene. Tone reproduction analysis, therefore, attempts to anticipate the appearance of the final positive transparency by considering the following:

- the brightness of the scene
- camera flare
- negative film characteristics
- camera exposure
- printing film characteristics
- printing exposure and processing

Since tone reproduction curves are generated in terms of radiometric (or photometric) characteristics, three commonly used units are defined in Table XVI.

Definition	Photometric Unit	Radiometric Unit
Luminous Flux (time rate of flow of radiant energy)	Lumen or Microlumen.	Watt or Microwatt
Luminance (flux per unit solid angle emitted per unit projected)	Foot lamberts or candles/ft^2	Watts/cm^2
Illuminance (luminance incident per unit area of a surface)	Lumen/meter^2 or meter/candle	Watts/cm^2 or cm watt

Table XVI. Photometric and radiometric definitions of radiance characteristics.

Since the photometric units are not applicable for wavelength regions outside the visible spectrum, it is best to employ the radiometric units when using either the ultraviolet or infrared spectral regions.

Tone reproduction is established by use of a graphical description consisting of four quadrants, each one of which represents a portion of the reproduction cycle. These quadrants are described in Figure 116.

Quadrant III Positive Material	Quadrant IV Final Reproduction
Quadrant II Negative Material	Quadrant I Flare Curve

Figure 116. Four quadrants of the tone reproduction diagram.

The procedure for determining the graphical descriptions for each quadrant will now be discussed.

Quadrant I — Flare Curve

Up until this point, it has been assumed that all the light entering the camera and forming the image has come from the illuminance of the scene; that is, if a density is measured on the film and transformed to the H & D curve, a numerical value is given to the log exposure forming that image.

It has been shown that:

$$E = I(t)$$

and the illuminance I is given by:

$$I = \frac{B\,T_L \cdot T_F}{4f^2}$$

Hence, film density was said to be produced from the object brightness. This is not *exactly* correct. Although most of the exposure (and the resultant density) comes from the object brightness, a small portion does not. At any point in the film plane of the camera, the illuminance (I), which forms the image, comes from two sources:

- the light from the object,
- extraneous light reflected from the lens elements, the barrel of the lens, etc. This light is known as *flare.*

Flare has the effect of casting a uniform fog or veil over the images and generally is so small as not to be noticed. Flare can sometimes be seen as a haze over one corner of the photo. Not all flare is caused by internal optical reflections, the object itself can contribute to the presence of flare, an extreme example of which is glitter reflected from the water's surface (see Figure 117). Although this is generally thought of as a specular reflection, the net effect is flare light on the film. We should naturally expect that this flare light would affect the shadows much more than the highlights. Suppose that in a negative the shadow area has a density of 0.18 and a highlight density of 2.6; also, assume a flare density of 0.18. The total densities for highlight and shadow are now 2.78 and .36 respectively. Notice that the density of the shadow has doubled, while that of the highlight is relatively unchanged. This situation prohibits one from saying "a density of x indicates an object illuminance of y".

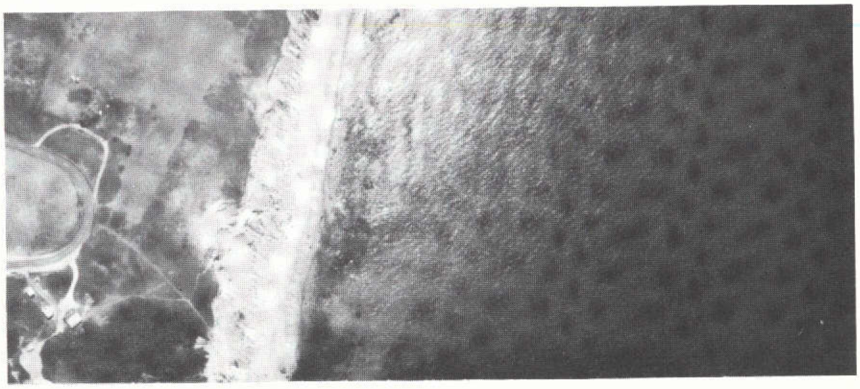


Figure 117. Flare can be produced by objects in the scene, as well as by camera components.

In tone reproduction, the effect of flare must be determined and it constitutes the first step of the process. To measure the amount of flare light in a camera, the following procedure is recommended:

- Set up a series of about five gray scale panels (reflectances of 4%, 8%, 16%, 32%, 64%) out of doors and at a distance sufficiently far away to be focused by the camera. Sheets of plywood, 4' x 8', covered with flat paint or a cloth work rather well.
- Mount the camera so that the panels will be about centered on the photo.
- At the time of exposure, the brightness of the panels must be measured with a standard photometer (B_1, B_2, B_3, B_4, B_5).
- Process the film and plot the H & D curve from the sensitometric wedge on the leading or trailing end. (It is assumed, by now, that step wedges are *always* placed on the film prior to exposure.)
- Measure the film densities of the step wedge which was placed in the scene and determine log E's of each step from the x axis, as shown in Figure 118.
- After taking the antilogs of these values, generate the ratios:

  $$\frac{E_2}{E_1} = E_2^1 \; ; \quad \frac{E_3}{E_2} = E_3^1 \; ; \quad \frac{E_4}{E_3} = E_4^1 \; ; \quad \frac{E_5}{E_4} = E_5^1$$
- Take log of E_2^1, E_3^1, E_4^1, E_5^1; $\log E_1^1 = 0$.
- Plot results of above against the log brightness of each panel as measured with the photometer; the curve will look something like Figure 119.

In Figure 119, the point S represents the darkest shadow (4% target), while H is the brightest highlight (64% target). This result is known as the flare curve and it occupies Quadrant #1 in the tone reproduction cycle, as shown in Figure 120.

Quadrant II — Characteristic Curve of Negative Material

The most important part of the H and D curve is the toe and straight line since highlights are rarely recorded up on the shoulder. To generate the correct characteristic curve for Quadrant II, use the same material which will be exposed in the camera. Cut a strip off the roll and place a sensitometric strip onto it. Certain precautions must be taken in doing this, however.

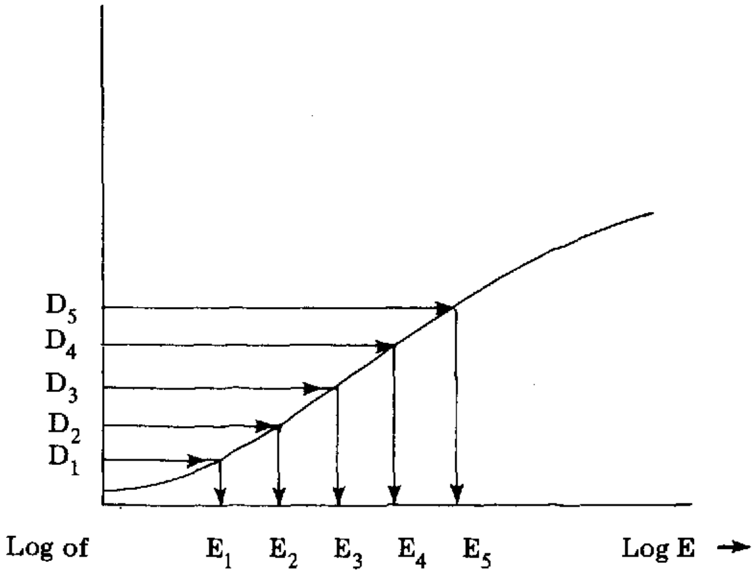


Figure 118. Density and log E values for scene gray scale.

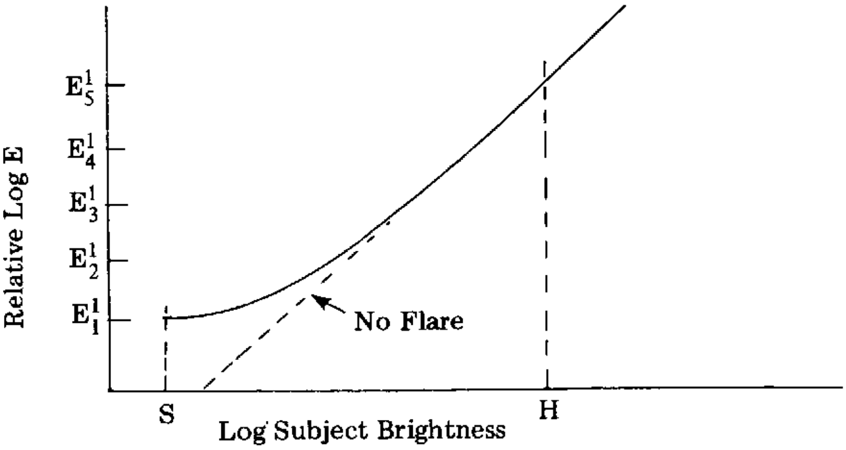


Figure 119. Typical camera flare curve.

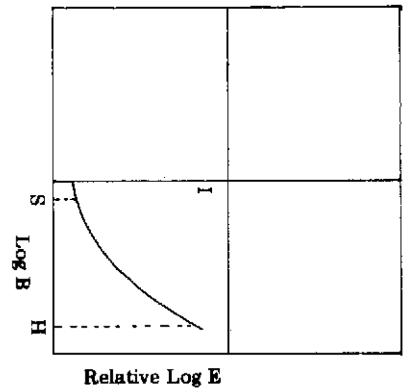


Figure 120. Tone reproduction diagram showing position of flare curve in Quadrant I.

- The step wedge must be exposed through the same multispectral filter as used in the camera.
- The sensitometric exposure time should be about the same as that used to expose the film in the camera.

The film strip is then processed exactly as the negative would be. From the density measurements made on the sensitometric strip, the D log E curve of Quadrant II is determined as shown in Figure 121. In the four quadrant tone reproduction diagram, this curve is oriented 90° counterclockwise with respect to the flare curve and is shown in Figure 122. Extending the line from S and H on the flare curve horizontally to intersect the negative characteristic curve shows the density difference which would result from imaging S and H on the negative material.

Quadrant III — Characteristic Curve of Positive Material.

The characteristic curve of the positive transparency material is determined in exactly the same manner as was the negative curve. The usual conditions of low minimum density and high gamma in the actual positive image require that the test film be exposed and processed in the same fashion. The position of the positive characteristic curve in the four quadrant reproduction diagram is somewhat unusual. The log E axis is horizontal, but the direction of increasing density is downward. Hence, the D log E curve of Figure 123, for the positive material, is oriented in the third quadrant as shown in Figure 124. The lines S and H are drawn upwards from the negative curve of Quadrant II to the positive curve of Quadrant III; extending the lines from Quadrant III towards the right to intersect the vertical extension of S and H from Quadrant I yields two points in the final tone reproduction.

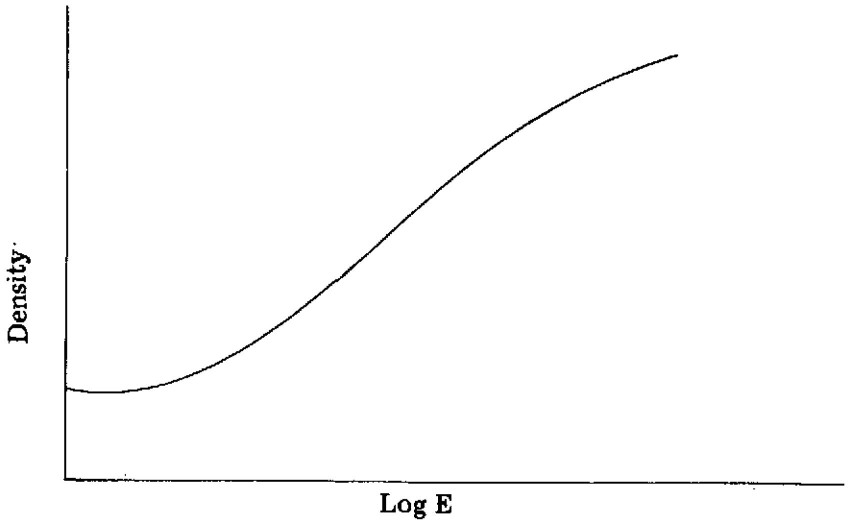


Figure 121. Characteristic curve of the negative material.

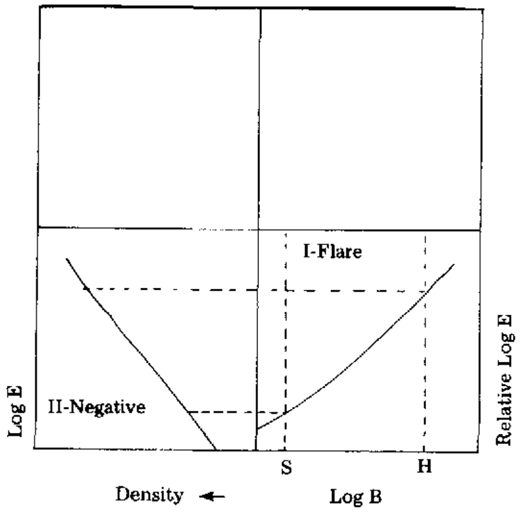


Figure 122. Characteristic curve of the negative material as positioned in the tone reproduction curve.

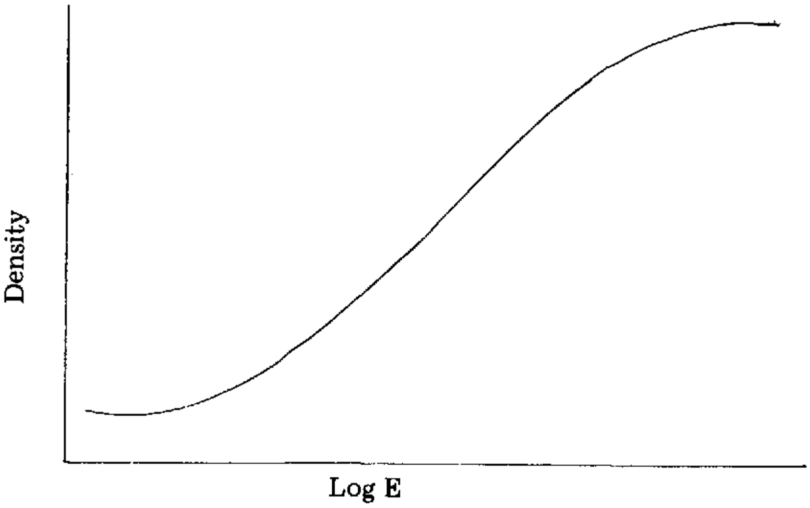


Figure 123. Characteristic curve of positive duplicating material.

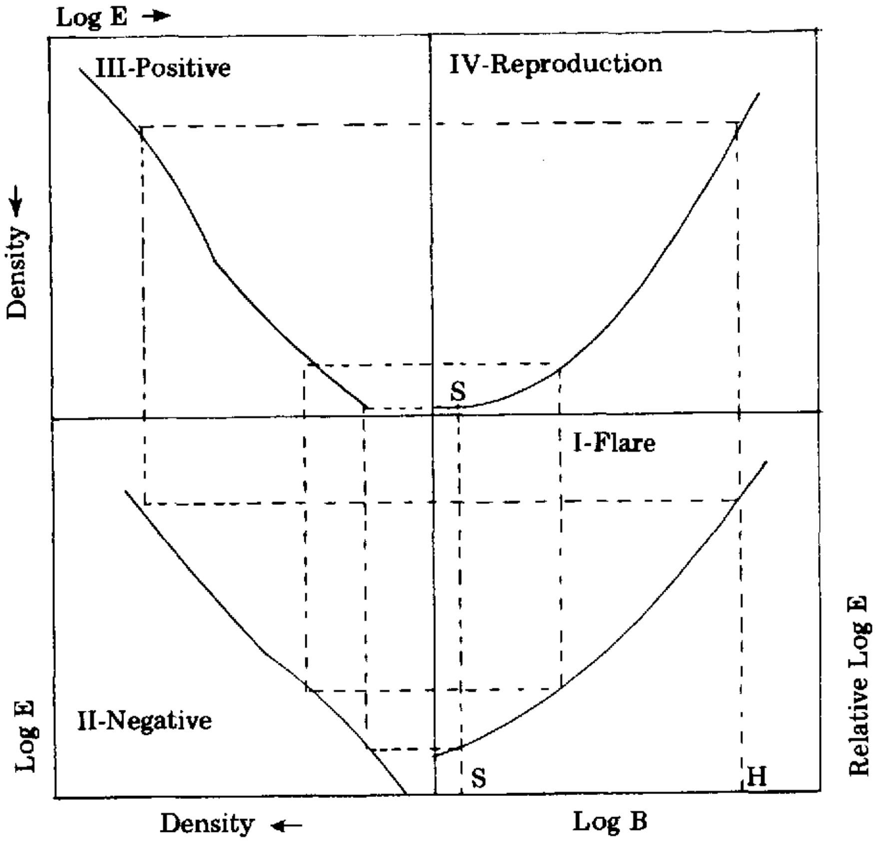


Figure 124. Final tone reproduction diagram.

Similar tracings for the intermediate points result in the final tone reproduction shown in Quadrant IV of Figure 124. An exact reproduction of the original scene would have produced a straight line at 45° to the axis in Quadrant IV.

The advantage of using this method of tone prediction is that it permits one to alter either the exposure, processing, or type of positive/negative films in order to produce a final Quadrant IV curve which is closer to the 45° straight line.

8.5 Summary

- Multispectral negatives are unsuitable for additive viewing which requires that they be printed into positive form.
- Eastman Kodak Type 2420 duplicating film is recommended for making multispectral positives.
- Projection printing allows correction for scale changes between multispectral records.
- Projection printing lenses must be well corrected for chromatic aberration.
- Contact printing with diffuse light increases photo contrast, but decreases resolution.
- Low base plus fog and low minimum density on positive multispectral records, produces high brightness in the multispectral viewer.
- Selection of printing gamma depends upon subject reflectance.
- Tone reproduction analysis permits one to alter exposure, processing, or films in order to produce desired results.

CHAPTER 9

ADDITIVE COLOR PRESENTATIONS AND THEIR MEASUREMENT

The final task associated with multispectral or additive techniques consists of synthesizing or recombining the separate images in an appropriate viewing device. The resultant color presentations are the end product towards which all previous efforts have been directed. Providing that all of the procedures for exposure, negative processing, and positive printing have been performed in accordance with the directives of the foregoing chapters, this final task will be the easiest to perform.

It is assumed for this discussion that the following equipment is available either "in-house" or on a rental basis:

- A four-channel multispectral additive color viewer incorporating hue, brightness, and saturation control of each projection system, as well as x, y motion of projection lenses for registration, and auxiliary scale correction lenses.
- A tri-stimulus colorimeter with a fiber optic probe for measurement of the color images.
- A set of viewing filters including red, green, blue, light blue or cyan, yellow-orange, and magenta. Two of each filter should be available to minimize interchanging between the projection systems.
- Chromaticity coordinate data sheets and diagrams. The exact configuration of these is dependent upon the instrument used.
- A list of the camera spectral bands most likely to produce the best multispectral results for a given set of ground objects.
- Two standard frames of imagery, i.e., one containing the ground reference panels and the second containing the ground truth test site.

9.1 Data Reduction Procedure

The following procedure is used to examine the multispectral imagery. It should be noted, however, that with sufficient experience with the additive viewer several of these steps may be eliminated.

1. Place the standard frame containing the ground truth site in the film plane of the viewer and bring down the platen to maintain the film in this plane.
2. Remove filters from each projection system and set the lamps to full brightness and full saturation.
3. Turn on each projection system (record) one at a time and adjust lenses to give good focus.
4. Turn on record #1 and record #2, inserting a red filter into record #1 and a green filter into record #2.
5. Fine focus record #1 for the red filter.
6. Using the x, y adjustments, register record #2 with respect to record #1. This process will perhaps require some small scale changes. Alter the scale of #2 and refocus the image. Note: Any change in scale usually requires a corresponding change in focus.
7. The images should display no color fringing in any portion of the format. (If fringing does exist, it is a clear indication of unmatched camera optics, unsynchronized shutters, or unmatched viewing optics. One is then forced into analyzing the imagery one area at a time.) Decrease the brightness of the first record #1, then #2, and recheck that no misregistrations are present.

8. Turn off record #2 and turn on #3, inserting a green filter into it. *Do not* touch record #1 either in x, y, or focus since this image is the one to which all others will be registered.
9. Repeat steps 6 and 7 for record #3.
10. Turn off record #3, turn on #4 using a green filter. Repeat steps 6 and 7.
11. Select those bands which are believed will produce the best multispectral imagery. If three bands are chosen, the least significant of the set should contain the blue filter. If only two bands are chosen, use a light-blue (cyan) and yellow-orange filter combination for viewing. Generally objects in the scene which reflect no differences in color (for the camera filters used) will then appear white or some shade of gray.
12. Select two or three types of ground objects to colorimetrically examine.
13. Alter the brightness and saturation of each record, in turn, until the maximum *visual* color difference is displayed between the ground objects of interest.
14. Measure chromaticity coordinates of the ground objects, record data, and plot.
15. Repeat steps 12 and 13 for the same object (target) groups. Often a small change in brightness or saturation level will expand the color difference between the objects for better discrimination.
16. Measure the chromaticity coordinates of the same types of targets over the whole format. Record the data, and plot. This process will yield a set of CIE coordinates which occupy small areas on the chromaticity diagram as shown in Figure 125.

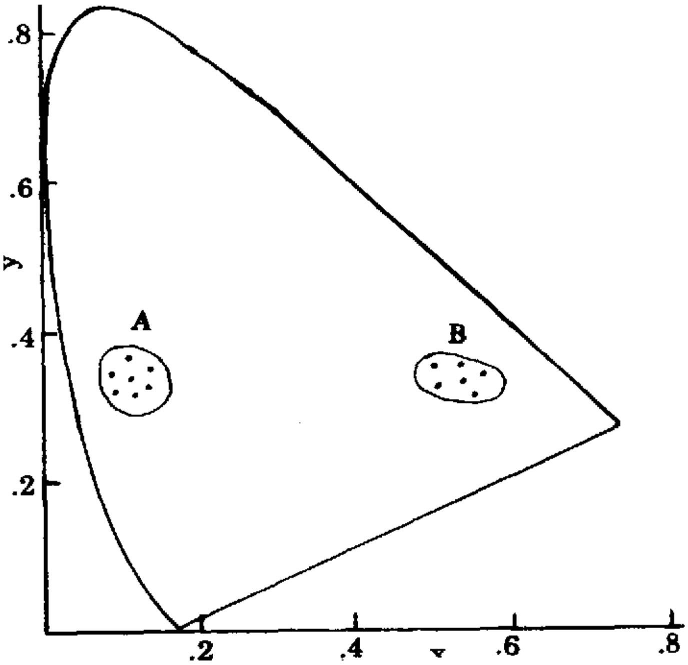


Figure 125. Color spaces occupied by classes of objects as measured from multispectral viewer screen.

17. Lift the platen and transport the film to the standard frame containing the gray scale and color panels in the scene. Measure the chromaticity coordinates of the white panel *without* altering any of the hue, brightness, or saturation controls. The data sheet containing the color measurement of the target types (step 16) must also list the CIE coordinates of the white panel measured under the same set of viewer conditions.
18. Select another group of two or three types of ground objects to examine colorimetrically.
19. Repeat steps 13-17.

20. Often a change in the viewing filters will enhance some object groups better than others. This is a matter of trial and error, although the red, green, blue, or cyan-orange combinations are usually best for a first-cut analysis.
21. Having determined the color coordinates which maximize the differentiation between objects in the scene and the color coordinates of the white panel associated with each, a table can be generated summarizing this set of photo-interpretation keys. See Table XVII.
22. On any other roll of film, exposed with the same set of camera filters, measure the x, y coordinates of the white panel, altering the hue, brightness, and saturation so that it conforms with the value in the Table XVII. The ground objects to be differentiated will then have CIE coordinates as shown.
23. Spot check results with ground examination.
24. Photograph viewer screen presentations for documentation and reference using a color negative film such as Kodacolor X or a color reversal film such as high-speed Ektachrome Type B.

Group #	Ground Objects Differentiated	CIE of Object	CIE of White	Multispectral Records Used	Filter
A	wheat	(.22, .183)			
	rye	(.171, .51)		1	Red
	tomatoes (flowering)	(.33, .15)	(.4, .51)	2	Green
	tomatoes (mature)	(.25, .29)		4	Blue
	bare soil (wet)	(.50, .35)			
B	bare soil (wet)	(.63, .28)			
	bare soil (dry)	(.3, .59)	(.5, .4)	2	Red
	sand	(.4, .5)		3	Green
C	balsam fir	(.2, .4)	(.34, .37)	1	Cyan
	red spruce	(.5, .3)		4	Orange

Table XVII

Table XVII. Color Coordinates of Ground Objects & White Standard Panel.

Since the standard panels are overflown several times in a roll of film at altitudes from which the actual multispectral imagery is exposed, correcting the white target to its predetermined color will remove any atmospheric effects from the imagery; that is, the white panel (and, hence, the ground objects) will appear *exactly* the same color regardless of the quality of the illuminant or the effects of altitude (haze, etc.).

9.2 Multispectral Viewers

Multispectral additive color viewers, like most optical devices, are supplied with various options and the general rule of "getting what you pay for" applies particularly to these instruments. That is, a relatively cheap model may not provide those features which will permit the photointerpreter to extract all the information which is contained in a set of multispectral photographs. A well-designed multispectral viewer will provide good registration and an even illumination over the entire format. Note: A good rule of thumb when considering multispectral viewers — whatever convenience is *not* built into the instrument will ultimately cost more in man-hours of effort. Providing only a few frames of data are to be analyzed at a time, extra effort may not be objectionable. However, when large volumes of multispectral imagery (for example, ERTS) are to be interpreted, the use of a more sophisticated additive color viewer will place the technician's efforts where they will do the most good — analyzing the photos, *not* trying to get the imagery to register or inserting the proper filters in place, etc.

The following considerations are essential to the selection of an additive color viewer:

- Format sizes acceptable.
- Hue, brightness, and saturation control.
- Registration correction.
- Parameters of projection lenses.
- Auxiliary scale correction lenses.
- Film transport and guiding mechanisms.
- Number of manual operations necessary.
- Cost.

Multispectral photography is presently being supplied in a variety of format sizes, depending upon whether the imagery is obtained using multiple camera arrays or a multiple lens camera. Current multispectral format sizes include:

- 70mm film chips
- 70mm film in cassettes
- 9½ inch pre-registered roll film

Since the cost of multispectral additive color viewers is still somewhat high, the projector selected should accommodate as many of these film sizes as possible. In addition, some units are available as rear screen viewers, wall projectors, or both. The choice of model is completely dependent upon the application or use of the imagery and the viewer cost.

The primary purpose of the additive color viewer is to present to the photo interpreter a composite multispectral image of the scene in good registration. Adequate registration accuracy of the photography can only be accomplished if the viewer incorporates four projection lenses which are well matched and possess little differential distortion. The lenses should be individually focusable in order to project each multispectral band at its maximum resolution. Any shift in the focus of one projection lens relative to the others will cause a change in the scale of the imagery. Hence, both focus and scale adjustments are essential in multispectral viewers. Some units provide for scale change only. In this situation the multispectral records are differentially *defocused* in order to facilitate registration of the composite. In addition to providing less than adequate resolution of each band, the imagery causes severe eye strain and is difficult to interpret for any length of time. Use of viewers providing matched scale, but less than optimal resolution, should be avoided. Matching the scale of the individual multispectral records is only one aspect of obtaining adequate composite registration.

When separate film chips or rolls are to be viewed additively, provision must be included in the projector to rotate and translate each multispectral image in x and y on the viewer screen. Movement of the projection lenses in x and y also allows correction for differential film shrinkage along the width of the film. Shrinkage along the length of the roll is generally negligible. x and y displacements may be accomplished by moving either the projection lenses or the photos in the film gate relative to each other. The former design is usually employed for x, y motion since the film is held flat with a platen arrangement which can accommodate a small amount of rotation.

Some film guide mechanism should be provided so as to minimize the extent of x, y lens motion required between frames. Optimally, one should be capable of registering the first set of multispectral photos on a roll of film, progress down that roll, and be required to make very little further adjustment in x or y and no adjustment in focus or scale to maintain registration. Viewing systems with good film guides are capable of this. The accurate tracking of multispectral roll film is also greatly facilitated by an automatic film transport operated in conjunction with a rheostat to control film speed. This provides an even transport of the film along the guides rather than the relatively jerky motions resulting from a manual crank arrangement.

The control of the color space in terms of hue, brightness, and degree of saturation is essential to an accurate interpretation of additive color imagery. A choice of *at least* three filters (red, green, and blue) per multispectral channel should be provided, as well as an open gate. Open gate brightness should be as high as possible in order to exploit the full scene brightness range of the composite screen image. Since the densities of the same image on each record add when viewed as a registered composite, inadequate brightness in the projector, will produce a loss of information in the shadows. Some viewers provide for decreasing the brightness of each multispectral channel by use of rheostats. Such an arrangement alters the color temperature of the lamps and, hence, the chromatic coefficients of the imagery. Viewers which provide neutral density filters for brightness control are a much wiser choice.

The color filters which are used in conjunction with each multispectral channel *must* be glass. Ordinary gelatin filters or gelatin sandwiched in glass are unstable in that they are very susceptible to fading and must be replaced at regular intervals. Heat (which is a normal consequence of burning four 500 watt lamps in a confined space) will also cause buckling of the gelatin and separation of the sandwiched filters. Placement of the filters in the optical system must be such that no degradation of the imagery occurs and the thicknesses of the filters should be varied to compensate for the change in refractive index at different wavelengths.

Desaturation is generally provided for by either the addition of white light to the filtered beam (by use of a beamsplitter and a second source offset by 90°) or by incorporating several red, green, and blue filters of varying levels of saturation in each optical system. The latter scheme is better in that the heat level within the machine is kept low thereby increasing the life of the projection lamps.

Naturally, the illumination across the entire format of the screen should be as even as possible. Fall-off in illumination across the field will amplify the low brightness in the corners of the imagery which may result from any vignetting effect of the camera. Lastly, convenient placement of controls, writing space, physical size, and power requirements should be considered. In conclusion, the minimization of manual control for filter selection, film transport, brightness, and desaturation will certainly facilitate a more rapid interpretation of multispectral imagery permitting the operator to alter the color space of each photo frame with the minimum of inconvenience.

9.3 Summary

- Multispectral additive color viewers should incorporate hue, brightness, and saturation control.
- Registration on viewer screen is performed using red and green filters.
- Two standard frames of data are required for initial colorimetric analysis of multispectral imagery — one containing a gray scale in the scene and the second containing the ground truth area.
- Multispectral viewer lenses must be selected for differential distortion and differential focal length.
- Even illumination across the viewer screen is essential for correct interpretation of multispectral imagery.

CHAPTER 10

CONSIDERATIONS IN THE SELECTION OF MULTISPECTRAL CAMERAS AND COMPONENTS

Once the filter, film, and exposure requirements have been determined, attention can be given to the multispectral camera lenses. A very large number of lenses are available from both domestic and foreign manufacturers and because of their high cost, considerable care must be taken to select the right one for multispectral use. Lenses are designed with a particular application in mind, i.e., projection, mapping, ultra-high resolution, aerial surveying, printing, etc. Generally, the lens selected for multispectral use must be a good quality aerial surveying lens which is manufactured in reasonable quantities, has a large maximum aperture (low f/number) and good resolution (140-200 1/mm). Since the ultimate use of multispectral imagery is in a *registered* composite additive color presentation, the selection of camera components must be geared to producing a *minimum* of misregistration between the records. In addition to the lenses, this includes shutters and the image motion compensation (IMC) device.

10.1 Multispectral Lenses

Regardless of whether one is using a multiple lens multispectral camera or several cameras in an array, *each* lens should have been supplied with certain data, including: flange focal distance, equivalent focal length, and lens distortion characteristics. Although angular coverage, aperture range, color correction, resolution, etc. are also important, it is only necessary to have this information when selecting the lens design. The *specific* lenses (i.e., serial numbers) must be chosen on the basis of calibrated focal length and distortion characteristics. Prior to purchasing any lenses for the multispectral camera, request a list of those available with their appropriate data and select the best four. This is the reason for only considering a lens which is manufactured in large quantities. Often, out of a possible one-hundred candidate lenses, only six or seven will be sufficiently close in specification to be used in a multispectral camera.

The definition of flange focal length and equivalent focal length are shown in Figure 126. Whereas the equivalent focal length is the distance between the rear principal plane of the lens and the focal plane, flange focal distance is a mechanical measurement. Every lens has a mounting flange with which it is attached to the camera body. The *exact* required distance from this mounting flange to the focal plane is called the flange focal distance and is usually given to .001 inch. The significance of focal length and flange focal distance will be realized if one considers a lens as being shaped like two prisms as shown in Figure 127.

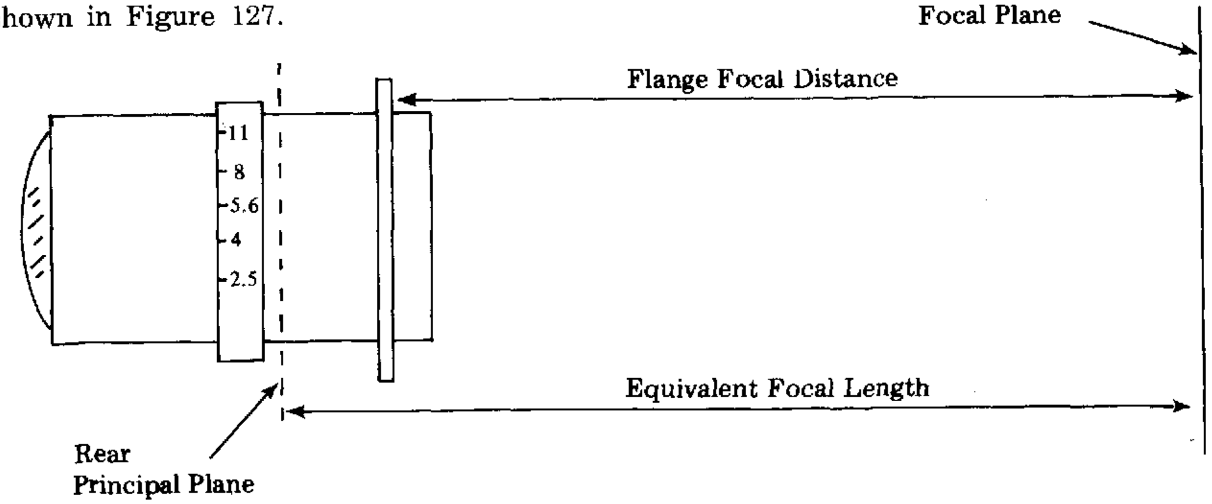


Figure 126. Lens diagram showing flange focal distance and equivalent focal length.

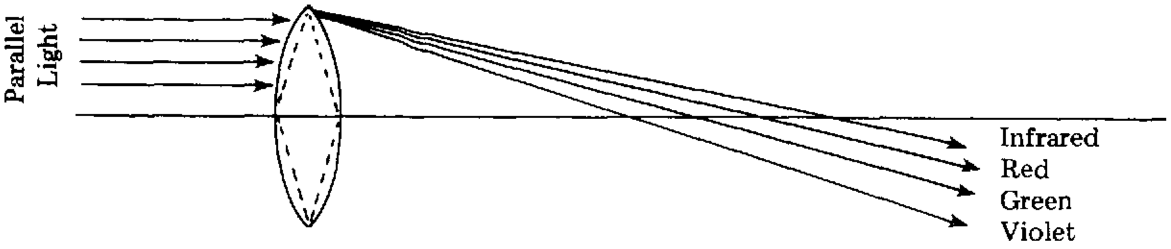


Figure 127. Focus changes due to wavelength of incident radiation.

A prism will bend incoming parallel light by different amounts depending upon the wavelength; blue light is bent more upon emergence from a prism than is red light. A lens (being shaped somewhat like a prism) does exactly the same thing causing blue light to focus at a shorter distance than the longer wavelengths of green or red. Lens designs have eliminated most of this error within the visible spectrum, although some residual usually exists. The back focal distance of a lens is generally measured using white light. Although blue light will still focus short and red will still focus long, white light focuses somewhere between these two (around green) and is called the equivalent focal length. The flange focal distance is a measure of the distance between the lens mounting surface and the focal point for white light. If one filters the lens, all wavelengths, except green or white (no filter), will be out of focus.

It is imperative then that some correction be made in the flange focal distances of the four multispectral lenses. The procedure is as follows:

1. Load the camera with a black-and-white film sensitive to the range of all filters being used (Note: IR sensitive emulsion is required if filters having bandpasses above 730 nm are used).
2. Place one filter over each lens.
3. Orient the camera so that it points at a sharp distant object. Taking the camera to the roof of a building and pointing it at distant (one-half mile) telephone poles, parked automobiles, fences, etc. is a convenient way to perform this test.
4. Take one photo; remove that strip of film from the camera and develop it.
5. Check that the exposure is not too light or not too dark to see the fences (or whatever) on each multispectral record. If the image is too dark, open the iris diaphragm and if it is too light, close the iris. *Save the film.*
6. Once the exposure is pretty well set, replace the camera in the same position on the roof.
7. Expose the film again; wind the film to a new frame.
8. Rotate *each* lens out one-half turn, expose and wind the film.
9. Rotate *each* lens out another one-half turn, expose and wind the film.
10. Repeat until each lens has been rotated out about three turns.
11. Process the film and label each frame as to the number of turns.
12. Examine *each* multispectral record at a time and select the one with the best resolution or focus for the *distant* object. (When the distant object is out of focus, nearby objects may be

very sharp. This situation is of no consequence since we are only interested in objects at an infinite distance away.)

13. Several focus situations can occur in the group of photos for each record. For example,

	Original Position	Out ½ Turn	Out 1 Turn	Out 1½ Turns	Out 2 Turns	Out 2½ Turns
Record A	Good	Excellent	Good	Fair	Poor	Poor
Record B	Good	Fair	Poor	Poor	Poor	Poor
Record C	Exc.	Good	Fair	Poor	Poor	Poor
Record D	Fair	Good	Excellent	Good	Fair	Poor

Record A — *Optimal* focus one-half turn out.

Record B — Good (not excellent) focus in original position.

Record C — *Optimal* focus in original position.

Record D — *Optimal* focus one turn out.

Record B may have attained excellent focus if it could have been rotated one-half turn *in.* A reliable machine shop can cut away a small amount of metal from the aft side of the mounting flange so that the lens will set closer to the film platen. Note: Although we have spoken in terms of rotating the lenses to provide for optimal focus in each band, this procedure is *strictly* not done. The one-quarter or one-half turn represents a distance depending upon the number of threads/inch and the lens should be *shimmed* out by the appropriate amount.

Actually, the lenses should have the same focal length for those parts of the spectrum which are covered by the filters; that is, one lens should be used strictly with a blue filter, another lens with a green filter, etc. The blue lens should have a white light focus *longer* than the white light focus of the red lens. In this way, the focal position of the blue lens for blue light will be the same as the red lens for red light. Consideration will now be given to the lens distortion.

Every lens has a nominal magnification associated with it and it also has small variations in magnification called distortion which vary with field angle. Distortion is a measure of the distance between: (1) the actual position of an image, and (2) the position the image would have if it were generated by a theoretically perfect lens. A typical distortion curve is shown in Figure 128.

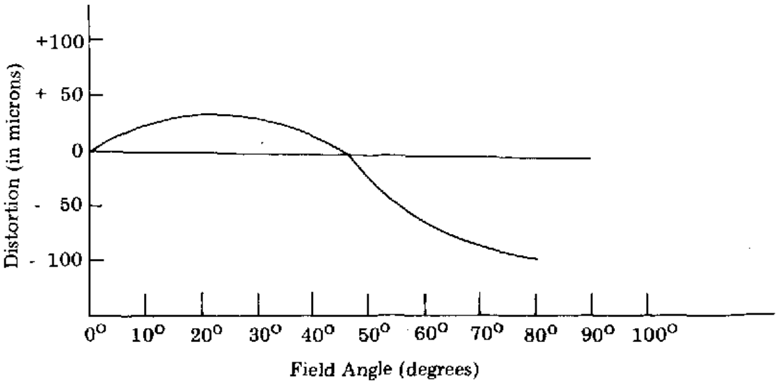


Figure 128. Typical lens distortion curve.

This curve shows that from 0° to 45° the lens exhibits barrel distortion; at about 50° the distortion is again 0, while from 50° to 80° there is a pin cushion effect.

Any distortion which is present in a set of multispectral lenses should be matched. This statement does not imply that the lenses must be distortion free. It merely indicates that whatever shape the distortion curve is for one lens, each of the other multispectral lenses should have the same shape. If they are not matched, it is possible that the situation of Figure 129 may exist. An image in one record could have a maximum distortion of +50 microns, while the same image on another record could have a distortion of -25 microns or a total distortion *difference* of 75 microns. If the lenses had the same distortion characteristics, the distortion difference would then be zero.

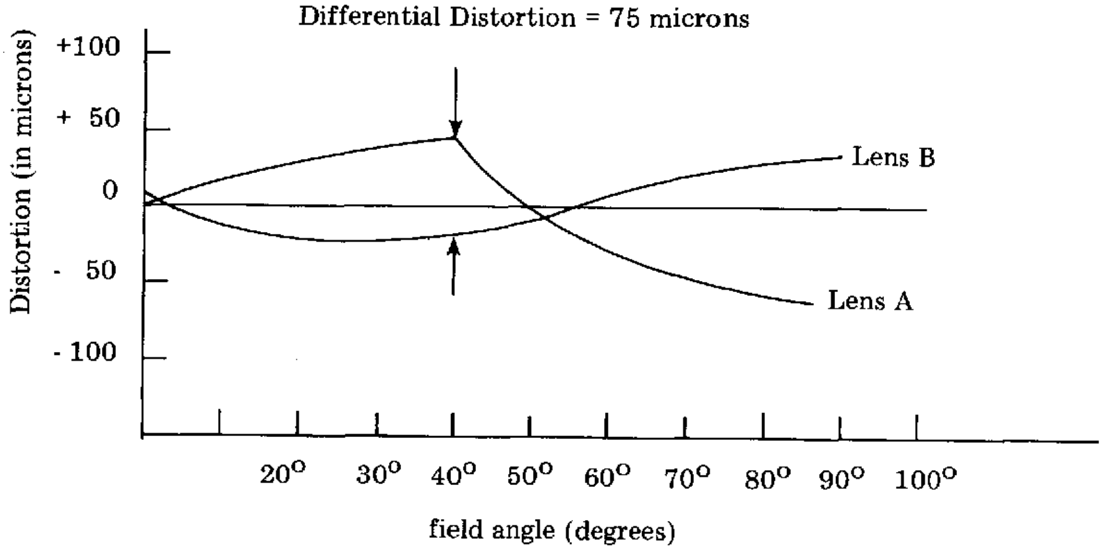


Figure 129. Positive and negative distortions will be added in final multispectral composite image.

To realize the significance of a 75 micron distortion between two multispectral records, it is necessary to analyze what effect it would have on the two photos registered in additive color on a multispectral viewer screen. Assume the viewer is a 4X system; 75 microns are approximately to .003 inches. Enlarging the imagery four times would make the screen error, or misregistration, .012 inches. That is, some portions of the combined image would have perfect registration, while other parts would possess a color fringing .012 inches wide and nothing could be done to eliminate it. In a 15 line/mm projected composite image, the .012 inch error would reduce the viewing resolution to 2 lines/mm in that specific photo area.

Assuming now that the lenses have been optimally focused and that their distortion characteristics have been angularly matched, their transmission as a function of wavelength should be measured in order to perform exposure calculations. This can be accomplished most conveniently with a spectrophotometer or if such an instrument is unavailable, the lens can be sent to a calibration laboratory. Lens transmission is measured every 5 or 10 nm from 380 to 950 nm and it is often helpful to measure its characteristics off-axis as well. If anti-vignetting filters are to be used, the lens transmissions must be measured with them in place.

10.2 Photographic Resolving Power

The ability of a camera to record fine detail in its imagery is usually expressed in terms of resolving power. Resolution is not necessarily the best test of image quality, but is a simple way to quantitatively compare various combinations of lenses and films.

The resolution of a film is generated by photographing a series of black lines on a white background with an extremely good quality lens. These black lines have an equal spacing between them, come in sets of three vertical and three horizontal lines to a group and the groups decrease in size in some regular way as shown in Figure 130. If the width in millimeters of a single line and a space in the smallest group which is resolvable in the image is called s, then its reciprocal is called resolving power in lines per millimeter:

$$\text{Resolution (1/mm)} = \frac{1}{s}$$

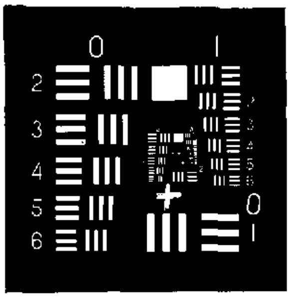


Figure 130. Air Force resolution target.

The resolution of a lens is generated by viewing the aerial image of a resolution target (such as that of Figure 130). In optical theory, the resolving power of a lens is a function of only the aperture and the wavelength of the radiation. Although most lenses do not follow this theoretical resolution law, at small apertures the visual resolving power does approximate it. For practical purposes, photographic resolution is a measure of the combined effect of both lens and film, expressing the quality of definition at the image plane. Hence, we are generally interested in the size of ground detail which will be visible at a specific altitude. To generate a complete resolution test of a camera, it is necessary to take photographs of a test target at several positions of focus and at several field angles. This may be done in the laboratory by using a highly corrected telescope objective as a collimating lens providing that: (a) the *focal length* of this lens is much greater than that of the camera lens, and (b) the *diameter* of the collimating lens is larger than that of the camera lens. Figure 131 shows a typical set-up for testing the resolution of a camera.

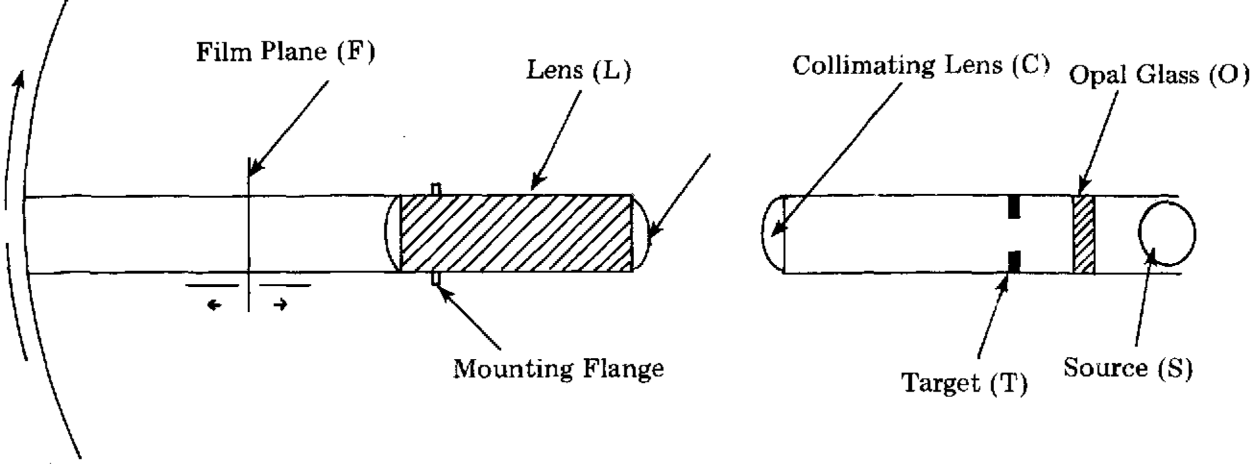


Figure 131. Laboratory collimator arrangement for testing lens resolution.

A transparent resolution test target T, mounted at the first focal point of the collimating lens C, is illuminated by the light source S. An opal screen, O, is provided so that the light is diffuse. The radiation emerging from the collimator will be parallel so that the test target appears to be an infinity distance away from the camera lens L. The lens L is mounted on a carriage which pivots about the vertical axis I. The film plane, F, moves along rails for focusing and care should be taken that the front surface of L is coincident with the pivot point I. Hence, the incident light can strike the lens L at different field angles. The focus position is visually set and a series of exposures are made on the same piece of film for different field angles. This process is repeated at various focus positions and the films are processed. The developed images are examined under a magnifier which will indicate the smallest group just resolved.

Suppose that the separation between centers of the lines in the smallest resolved group is W in the original target T. If the focal length of lens L is F_L and that of the collimating lens C is F_C, then the resolution of the on-axis image is:

$$\text{Resolution}_{\text{Axis}} = \frac{F_C}{(F_L \cdot W)}$$

The off-center images become larger with increasing field angle so that at any angle θ, the resolution of the radial and tangential lines is:

$$\text{Resolution}_{\text{Radial}} = \text{Resolution}_{\text{Axis}} \cdot \text{Cos}\ \theta$$

$$\text{Resolution}_{\text{Tangential}} = \text{Resolution}_{\text{Axis}} \cdot \text{Cos}^2\ \theta$$

The definition of radial and tangential resolution patterns is shown in Figure 132. (It should be noted that lenses up to about 40 inches can be tested using a 100-inch collimating lens.)

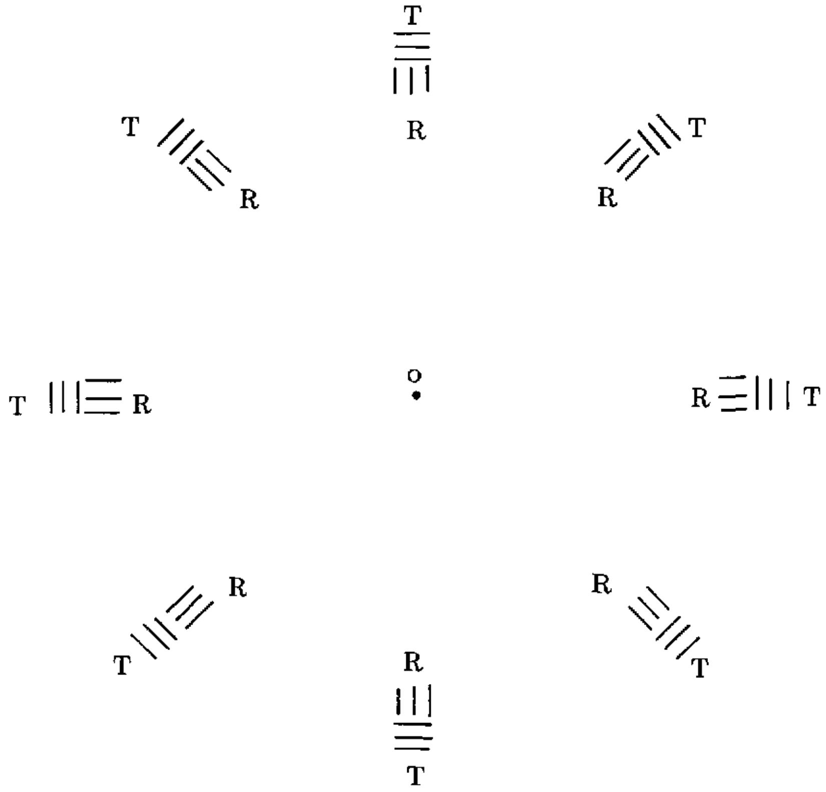


Figure 132. Radial resolution patterns are those which radiate out from optical axis o; tangential patterns are perpendicular to radial.

To determine the ground resolution from the camera resolution just described, the following relationship is used:

$$\text{Resolution}_{\text{Ground}} = \frac{A}{F_L\,(25R)} \text{ in feet}$$

where A is the flight altitude in feet

F_L is the camera focal length in inches

R is the camera resolution in lines/mm

25 is the factor which converts R to lines/inch

Thus, if a six-inch lens has a resolution of 40 1/mm, then from 20,000 feet it resolves details which are 3⅓ feet apart. Naturally, lenses which are to be employed using filters should be tested with the filters in place.

According to optical theory, the resolution of an image should decrease with increasing f/number as shown by the dotted line in Figure 133. The photographic resolving power, however, does exactly the opposite; that is, the resolution increases with increasing f/number up to some maximum point whereupon it begins to decrease. Further examination of Figure 133 shows the decrease in resolution with: (a) lower contrast between the target and background, and (b) with the use of coarser grained films. Also, notice that the *maximum* resolution shifts to higher f/numbers as the grain of the film becomes coarser. Although Figure 133 is a generalization, all aerial lenses regardless of their focal lengths, apertures, or field of view have resolution characteristics similar to these.

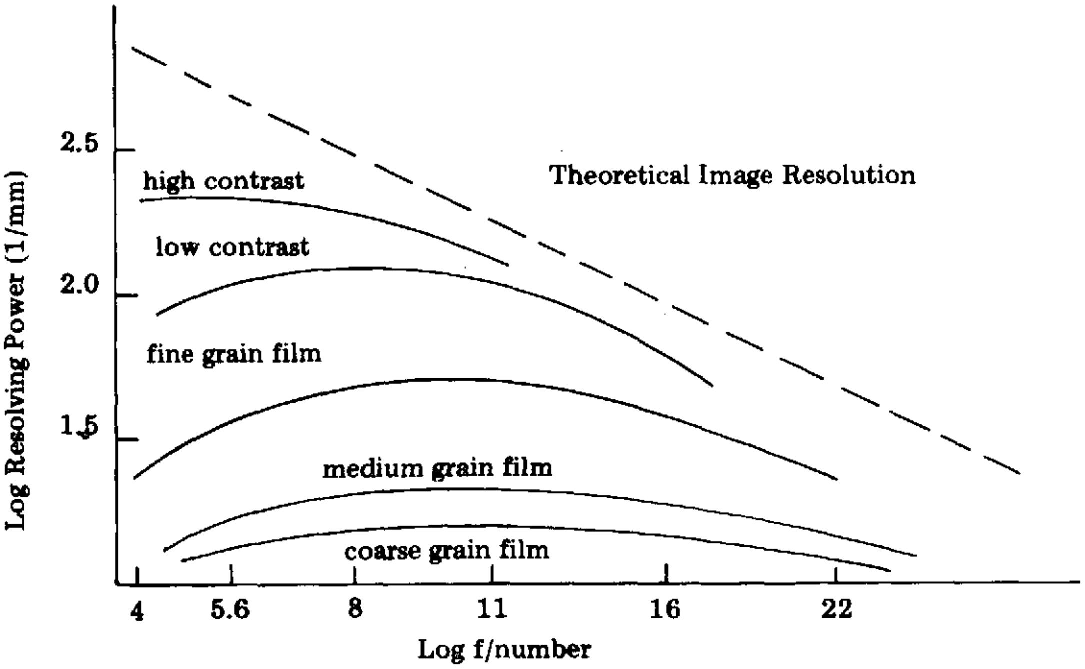


Figure 133. Comparison of axial resolving power for high and low contrast and different grain films.

The resolving power obtained for a given film and lens combination in actual aerial photographic tests is greatly dependent upon the contrast of the scene, exposure, and processing. Since the resolution of a camera varies exponentially with contrast, it is imperative that the camera be tested with resolution targets of about the same contrast as that which will be encountered in actual flight. The presence of atmospheric haze must also be accounted for since it reduces the contrast of the scene thereby reducing resolution. As a matter of fact, the loss of contrast not only makes larger details difficult to see, but also causes some objects to disappear from the image altogether.

The effect of haze is to reduce brightness differences of all objects in the scene by the same amount, the detail in the shadows being lost first. For example, suppose background and targets had log brightnesses as shown in Table XVIII and the same contrast (0.2).

Background	Target
0	0.2
.2	.4
.4	.6
.6	.8
.8	1.0
1.0	1.2
1.2	1.4
1.4	1.6

Table XVIII. Log brightness of hypothetical background and target.

If these subjects are seen through a haze so that 20 percent of the maximum brightness is added to each brightness, the new range of log brightness is now 0.73. The contrast of the first step decreases from 0.2 to 0.27, while the contrast of the eighth step only drops from 0.2 to 0.159.

Resolution and contrast also decrease at very high altitudes. As the camera-to-subject distance increases, the size of the images is decreased according to the laws of optics. However, an altitude will be reached at which the images are as small as the lens is capable of producing them. With increasing altitude, then, the image size will remain the same, but less light flux will enter the lens resulting in a decrease in contrast. At very low exposure levels, the resolution is limited primarily by the lack of contrast since the slope of the toe portion of the characteristic curve is quite small. As exposure is increased, the contrast and resolution also increase until the maximum is reached at the beginning of the straight line. No further increase in contrast takes place, although the grain of the film does increase with density. The net effect, therefore, is that resolution begins to drop off after it reaches its maximum due to graininess. Naturally, the resolution fall-off would become more rapid near the shoulder of the H & D curve.

Slow emulsions generally have a finer grain and better resolution than the faster types, although this does not mean that they are best for aerial photography. Slower emulsions require longer exposure times (either in terms of aperture size or shutter speed) and this may not be practical from an operational point of view. In order to minimize image motion, the shutter speed should be kept fast, while the exposure is increased opening the lens aperture. The result is that while the resolution is increased by using a less grainy film, the lens resolution is *decreased* by using a larger aperture. Hence, the overall resolution will be increased by a small amount or may actually decrease depending upon the actual lens and emulsion used. Generally, only a small area around the center of the photo will show any marked improvement by using a finer grained film.

Graininess of a film can be reduced by cutting down on the development time. However, this also results in a decrease in contrast and speed which may actually reduce the final image resolution. It should be noted that printing a positive on a contrasty film will not reveal details which are not already visible in the negative. It may, however, improve the general appearance of the photo and make interpretation easier by increasing the contrast on the broader areas of tone. Multispectral imagery combined additively in a color viewer will give a marked increase in resolution, as well as a reduction in graininess. This is primarily due to the fact that negatives consist of graininess patterns which are a *random* distribution of densities. Superimposing several images will cause a build-up of the image details, each one re-enforcing the others to a full strength image, while the random density differences tend to cancel each other.

Image motion also contributes to the loss of photo resolution. These motions are caused by the vibratory movements and the steady forward speed of the aircraft. This first motion is readily eliminated by using a stabilized mount for the camera. The effect of forward motion on the resolution of ground images is most serious at low altitudes and large scales. Although the most obvious way to eliminate this is to reduce the camera exposure, the limited sensitivity of films makes this method impractical. The brightness of shadows is much less at low altitudes than at high and so more exposure is required. Most lenses do not have a sufficient range of f/numbers to cope with the required shorter exposures while still producing a well-exposed negative.

The blur, B, due to the uncompensated image motion can be calculated from:

$$B = \left(\frac{V}{H}\right) F \cdot t$$

where: F = effective focal length
t = exposure time
V = aircraft velocity
H = aircraft altitude

It should be noted that the ratio (V/H) affects the dynamic resolution. The dynamic resolution is approximately inversely proportional to the ratio V/H. The expression governing this relationship is given as:

$$R_d = \frac{R_o}{2R_o\left(\frac{V}{H}\right) + 1}$$

where: R_d = dynamic resolution
R_o = static lens-film resolution

Substituting the parameters of velocity and altitude into the above expressions, the dynamic resolution of the uncompensated image can be determined. For example, if static film-lens resolution, R_o, is 45 line pairs/mm, then for the aircraft flying at 150 mph and at an altitude of 15,000 feet or less, i.e., V/H = .015 or greater, image motion compensation should be provided if a resolution of 20 line pairs/mm or greater is desired. Motion of an image may be stopped by either moving the film in the camera or by tilting the camera axis during exposure so that the optical axis of the lens continues to point at the same object. The required motion compensation for a moving film is:

$$\text{Film Speed} = \left(\frac{V}{H}\right) \cdot F$$

where: V = aircraft velocity in ft./sec.
H = aircraft altitude in feet
F = focal length in feet

For example, if V = 300 mph = 440 ft./sec.
H = 200 ft.
F = 6 inches = .5 ft.

$$\text{Film Speed} = \frac{440}{200} \cdot \left(\frac{1}{2}\right) = 1.1 \text{ ft./sec.}$$

10.3 Characteristics of Multispectral Filters

The spectral characteristics of reflected light are altered by the use of optical filters which may be fitted onto the front of a camera lens. Such filters absorb a portion of the incident radiation either selectively or non-selectively regardless of whether such radiation is to be transmitted through or reflected from the filter surface.

Selective absorption filters have a distinct color associated with them dependent upon the nature of the dye molecules which have been incorporated into the base or support (gelatin, glass, plastic, liquid, etc.). Most absorption filters have a rather arbitrary set of color numbers associated with them so that examination of their transmission properties is necessary to determine their ability to absorb light. From such data, an example of which is shown in Figure 134, both the peak transmission and bandwidth can be determined. The bandwidth is actually the range of wavelength which is *not* significantly absorbed by the filter. To determine the bandwidth draw a horizontal line at that value of transmission which is equal to 50 percent of the peak transmission on the filter curve. This line will intersect the filter curve at two points and the difference in their wavelengths is the bandwidth.

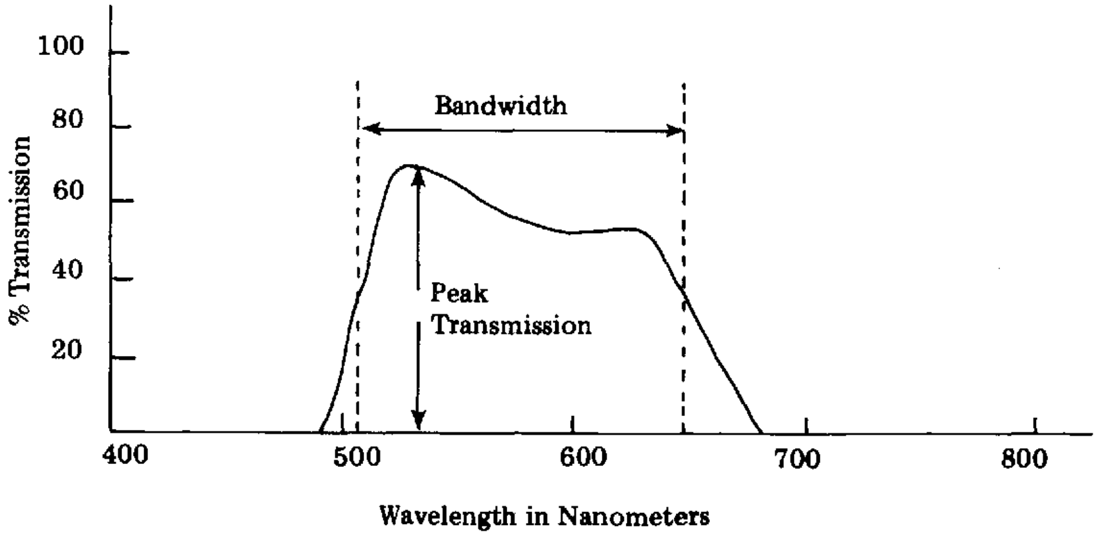


Figure 134. Definition of filter peak transmission and bandwidth.

Non-selective absorption filters (also called neutral density filters) serve to reduce the overall amount of light reaching the film by the same amount. With many such filters this does not happen. They have been found to absorb blue light and transmit more infrared light than their nominal transmission values quote, as shown in Figure 135 for the Wratten #96 series.

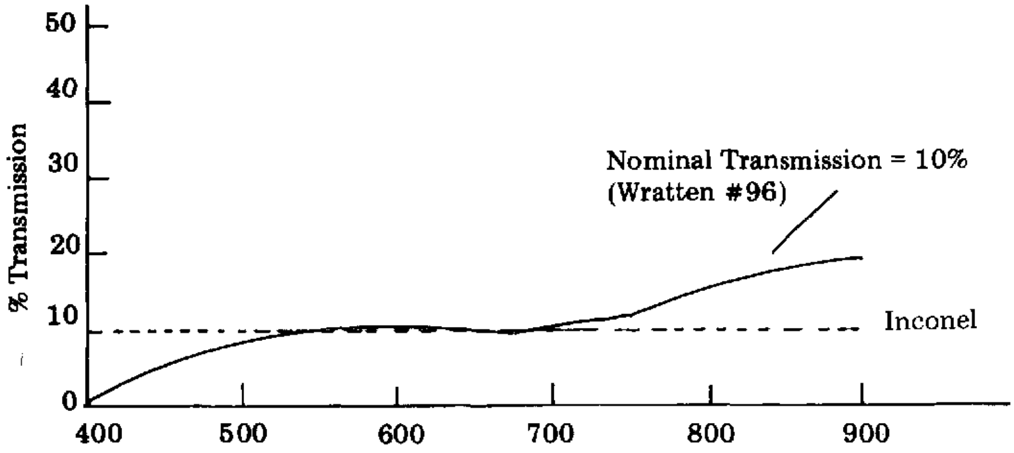


Figure 135. Absorption characteristics of Wratten #96 and Inconel coated neutral density filters for visible and near infrared spectral regions.

For critical multispectral, as well as color photography one should employ an Inconel coated density on glass as a non-selective filter. In addition to ordinary dye absorption filters, another type is commonly used in multispectral photographic applications—namely, interference filters. These filters are based on the principle that light reflected from two surfaces separated by a small distance will be cancelled when they meet out of phase. The path difference between these reflections is optically equal to an odd number of half wavelengths of the light cancelled. Such filters have the following properties:

- The maximum percent transmission is extremely low, often only as high as 2-4,percent.
- They possess very narrow bandwidths
- The wavelength of the transmitted light varies with both the angle of incidence and the temperature of the substrate.

By replacing the silver layers in these conventional interference filters with alternate coatings of materials having high and low indexes of refraction, the filter will have a high peak transmission, 80-90 percent, with relatively narrow bandwidths (say, 10 nm). The high index material ($n = 2.4$) and the low ($n = 1.4$) are evaporated onto glass and as many as fifteen to twenty layers, one-quarter wavelength in thickness, may be applied. The quality of the filter generally improves with the number of layers and can be made to transmit infrared radiation, as well as visible.

There are two major sources for absorption and interference filter inefficiencies:

- Loss due to surface reflections
- Absorption in regions where there should be none
- Non-absorption in regions where there should be absorption

An uncoated surface of every filter reflects about 4-5 percent of all light which strikes it, regadless of the wavelength or type of construction. Hence, for a single filter a total of between 8-10 percent of the light is lost because it contains two surfaces; coating the filter in the same way that a lens is coated will reduce the transmission losses to about 1 percent per surface however.

A theoretically perfect filter should have a square wave shape as shown in Figure 136a. Although this condition can be approximated, this ultimate shape is never achieved. The peak transmission can be increased up to 95 percent, but only at the expense of the side slopes as shown in

Figure 136b. Conversely, the slopes can be made quite steep, but the peak transmission will decrease accordingly (Figure 136c). Such inefficiencies are unfortunate but cannot be eliminated while maintaining the spectral characteristics desired.

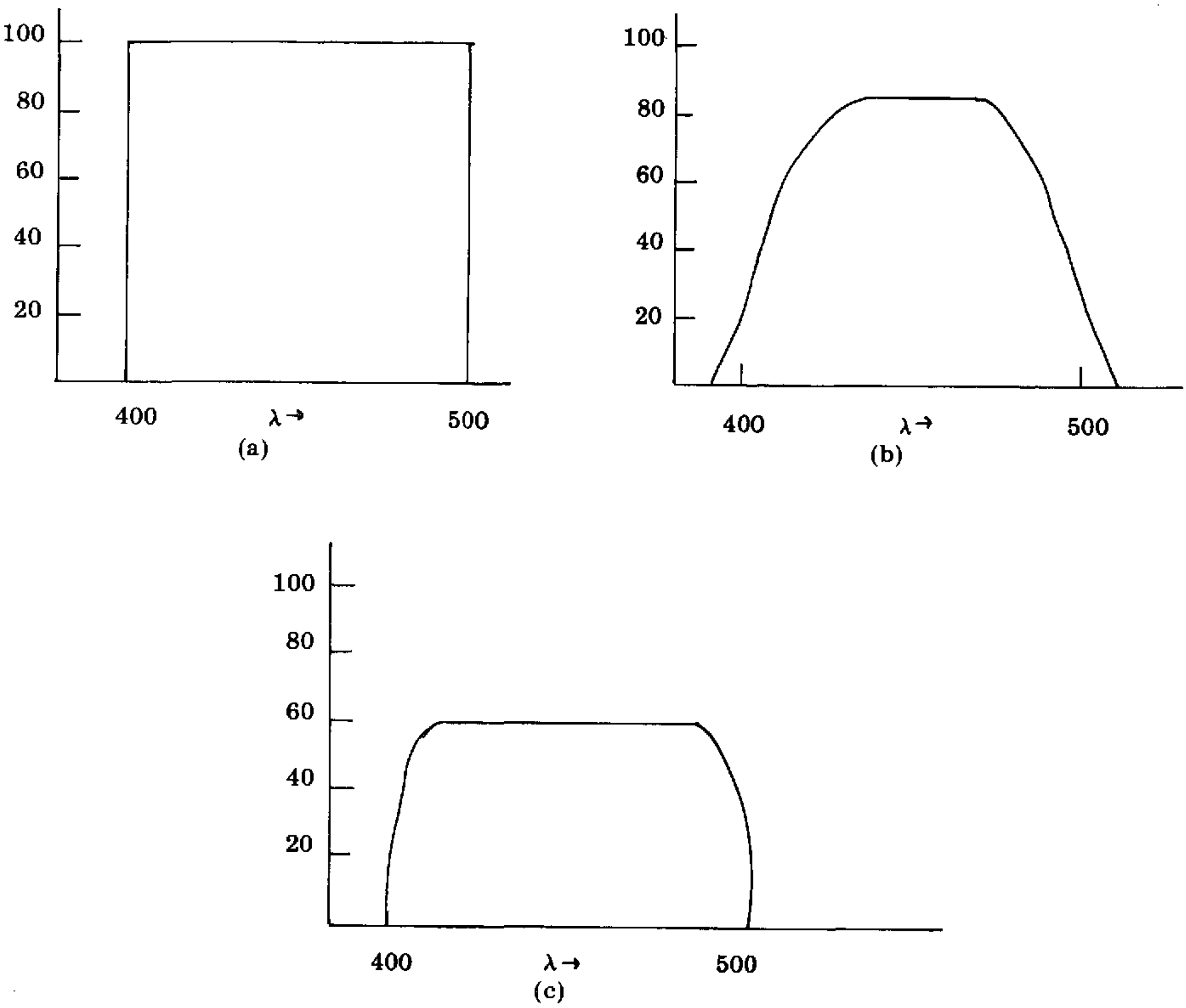


Figure 136. A theoretically perfect absorption filter should have a square wave shape (a); large transmission can be obtained by decreasing the side slopes of filter (b); steep side slopes necessitate drop in peak transmission (c).

Some photographic applications require the use of more than one filter to achieve the spectral absorption required. In such cases, the filters should be cemented together, thus minimizing the surface reflection losses. For example, if three filters are to be used in combination, the surface losses when they are *not* cemented are about 30 percent, while they are only 10 percent for a cemented combination. Light losses of this magnitude will present definite exposure problems when a relatively slow film is used in the camera. In order to calculate the effect of combining several filters, the transmission of each filter is multiplied wavelength by wavelength and the following will be noticed:

- The peak transmission is decreased
- The bandwidth has become narrow

It should be noted that using absorption filters in conjunction with the lens for multispectral photography will not only alter the response of the film, but a contrast change will take place if no compensation is made in the development process. Generally, a decrease in contrast takes place if a blue filter is used and an increase in contrast is seen when a red or near infrared filter is used. Care should be taken that all lenses are focused with the filters in place since a thick filter will change the effective focal length of the lens.

10.4 Shutters and Shutter Timing

There are two basic types of shutters used in photographic cameras — between-the-lens and focal plane — each one of which has its advantages for particular applications. As the name implies, between-the-lens shutters are located in the air space between the front and rear lens elements. The light is admitted by the opening and closing of blades made of some thin metallic material. These blades are arranged so that they open from and close towards the center. Focal plane shutters consist of an opaque, flexible curtain which is positioned just in front of the focal plane. The light is admitted through a slit in the curtain across the line of film motion. The curtain is tensioned between two rollers which pull the slit across the film at various speeds.

Between-the-lens shutters are primarily used in single lens multispectral systems and in single cameras making up a multispectral array. Tests have shown, however, that the synchronization of a set of shutters is far from perfect. That is, although each mechanism is fired off the same intervalomter, there exists a time lag between the closing of the electrical circuit and the instant that the shutters operate. This time lag (which differs for each lens shutter) can introduce drastic misregistrations into the final multispectral images. (The effects of forward motion of the aircraft are not being considered — it is assumed that some form of IMC device is being used.) The cause of image displacement comes from two sources:

- The random vibrations of the aircraft
- The motion of objects on the ground

It is obvious that considerable angular velocities are developed when a photo plane goes into a steep turn; however, in bumpy air there will be continual violent movements which drastically produce additional angular velocities of pitch, roll, and yaw. The magnitude of these irregular movements depend upon the aircraft characteristics, pilot skill, as well as the air conditions. Hence, lack of synchronization between shutters which are supposed to expose simultaneously will shift the nadir on all multispectral records. Providing that this is the only "motion error", it can be removed in the viewing stage by altering the x, y positions of the multispectral records relative to each other. This assumes, of course, that each image exists on a separate piece of film.

When objects in the scene are themselves moving relative to the terrain, a lack of shutter synchronization will produce a set of misregistered multispectral images which cannot be corrected. Assume that at some time t, a vehicle (for example), is moving at some velocity v along the ground and is photographed with a multispectral camera equipped with an IMC device. If a time lag of Δt exists between the synchronization of the shutters, then the image displacement of the moving vehicle on the multispectral records will be:

$$d = \frac{vf}{H} (\Delta t)$$

where: v = the vehicle velocity
f = the camera focal length
H = the altitude
d = the image displacement

Stationary objects, however, will still be in register so that superimposition of the images will produce either:

- Registered overall scene — moving vehicles misregistered
- Registered moving vehicles — misregistered overall scene

Hence, in multiple camera arrays one of the units should contain a "master" shutter, while the remaining cameras contain "slave" shutters. Whereas the master is equipped with a complete shutter mechanism, the slaves have only a diaphragm and shutter blades which are coupled to the master and controlled by it.

Multispectral cameras which employ a multiplicity of lenses in a single body often incorporate focal plane shutters. One should note that in such cases individual shutters are not used; rather a single curtain is constructed in which not one, but four, slits exist. It can easily be seen that each part of each image is being exposed at exactly the same instant so that regardless of erratic aircraft motion there is no differential positioning of nadir. Also, since the synchronization between the slits is perfect, no misregistration will occur due to the movement of objects in the scene. Since ease of interpretation is directly related to the resolution or registration of the final composite image, focal plane shutters with multiple slits should be used for multispectral photography wherever possible.

10.5 Four Lens Multispectral Camera Vs. Four Camera Multispectral Array

The choice of using either a four-lens camera (FLC) or a four-camera array (FCA) for multispectral photography has been a topic of discussion for the past decade. The use of more than four lenses in either configuration will not be presented since these systems require elaborate data reduction equipment and the number of photo combinations becomes extremely large making them impractical for most multispectral photography.

Both the FLC and FCA systems have their advantages and disadvantages which may be classified according to the three stages of the multispectral additive technique; i.e., exposing, processing, and viewing.

Four Lens Camera	Four Camera Array
Exposure	
Usually designed so that they accept only one type of film at a time for all multispectral records (some units, however, have a modified magazine which will accept four rolls of 2.125 inch wide film).	Four separate film magazines permit exposure on multiple types of black-and-white film or color emulsions or a combination of both. Also individual magazines can be interchanged during flight for comparison of film response, etc.
Use of a four-slit focal plane shutter assures identical exposure time on each record and identical spatial positioning of all images relative to the principal point of the lens.	Use of between-the-lens shutters introduces synchronization errors, both in terms of length of exposure time and time lag between the actual exposure of each record.

Four slits in a focal plane shutter assure synchronization and are relatively easy to construct.	Exact synchronization of between-the-lens shutters requires elaborate design and construction.
Lenses aligned in a single body can be pinned so that it is relatively easy to maintain orthogonality of optical axis and focal plane.	Difficult to maintain precise vertical alignment between individual cameras.
Only one moving camera or moving film IMC device required.	Four moving cameras or four moving film IMC devices required.
Exposure changes can be made only using diaphragm of each lens.	Exposure can be varied with both aperture and shutter timing of each camera providing a wider latitude for scene brightness.
Processing	
Processing four images on a single film yields differential gammas between records necessitating detailed printing procedures for correction.	Processing of each multispectral negative can be tailored so as to exactly match gammas.
Viewing	
Alignment and film guide mechanism in camera can be made compatible with viewer so that composite multispectral imagery is automatically registered. One registers only the first frame, each of the subsequent frames on the same roll will be then in register.	Each multispectral record must be manually aligned with respect to the others for *each* frame viewed.

10.6 Summary

- The primary variables with which multispectral lenses are selected are: focal length, flange focal distance and distortion.
- Flange focal distance must be changed for each filter.
- Thorough focus tests must be performed with filters in place.
- Multispectral lenses should possess a minimal amount of differential distortion between them.
- Photographic resolution depends upon both the film and lens.
- Resolution is a function of both film graininess and image contrast.
- IMC devices should be employed on all multispectral camera systems.
- Multispectral absorption filters are often a compromise between maximum transmission and side slope.
- Neutral density filters should be tested in near infrared before being used in camera.
- Bandpass of interference filters changes with angle of incidence and filter temperature.
- Combinations of filters for a single lens should be cemented together to minimize reflection losses.

- Focal plane shutters and between-the-lens shutters are generally used for multiple lens and multiple camera multispectral systems, respectively.
- Shutter synchronization determines in part the ultimate registered resolution of the multispectral composite image.

CHAPTER 11

PHOTOGRAPHIC MATERIALS FOR COLOR AND BLACK-AND-WHITE PHOTOGRAPHY

The proper selection of a film for color and/or multispectral aerial photography is of paramount importance because of the time and money expended in obtaining good aerial negatives. Hence, one should have a knowledge of the film characteristics which are included herein and which were discussed in Chapter 6. Although most aerial emulsions are rather versatile, there is usually one which is most suited for a particular application. Examination and comparison of film properties will help in choosing the right emulsion for the photographic mission to be done.

The following are brief descriptions of the film characteristics which will be given in the data sheets of this chapter.

— Characteristic Curve: The way an emulsion responds to exposure and development is most usually observed by plotting its characteristic curve. To obtain this curve, the material is given a carefully controlled exposure through a step tablet in an instrument called a sensitometer. Development of these exposures under very carefully controlled conditions yields a gray scale with a series of steps that differ in density.

The amount of exposure that was given to each step is specified in terms of the light intensity multiplied by the length of time the material was exposed. Density (D) is plotted versus the logarithm of exposure (log E). The characteristic curve, or D-log E curve, reproduced in the data sheets represents the average product exposed and processed under normal conditions. The slope of any part of the curve indicates how rapidly the density changes with changes in exposure. Also the shape of the characteristic curve varies with different emulsions.

— Spectral Sensitivity: The spectral sensitivity of an emulsion describes its response to radiations of varying wavelength in the visible and invisible parts of the spectrum. It is possible to extend the sensitivity through the green (orthochromatic sensitization), through the red (panchromatic sensitization), and into the invisible infrared region of the spectrum.

Spectral sensitivity, or color sensitivity, is an important consideration in choosing a film for a particular use. It determines the kind of filters that can be used with the material and the way the film must be handled in processing.

Which filters you can use with a particular film depends, of course, on the color sensitivity of the emulsion. For example, a red filter can be used only with a red sensitive, or panchromatic film.

Except for materials made for special purposes, Kodak films are divided into the following four sensitizing classes:

1. Blue Sensitive — films having only the blue and ultra-violet sensitivity inherent in any silver halide.
2. Orthochromatic — this class is sensitive to green, as well as to blue and ultraviolet.
3. Panchromatic — these films are sensitive to red, green, and blue, as well as to ultra-violet.
4. Infrared — these films are sensitive to ultra-violet, blue, red, and invisible infrared radiation.

— Reciprocity Effect: Although the reciprocity effect is insignificant in most ordinary applications of black-and-white photography, some lighting conditions require abnormally long or abnormally short exposures. Then the effect can be seen as underexposure, a change in contrast, or both.

Films made for different purposes have different reciprocity characteristics. Therefore, when you select a film for use in a situation where you can foresee that exposures may be very long or very short, select a film with reciprocity characteristics that suit the application. To enable you to do this, tables of adjustments in both exposure and development to compensate for reciprocity effect are given in the data sheets.

— Graininess: The densities in a black-and-white negative are composed of microscopic grains of silver which tend to clump together and form the familiar granular pattern that becomes visible when a negative is enlarged. As a rule, the faster a film is, the greater its tendency towards graininess. Although each emulsion has an inherent graininess, this can be decreased by using an effective fine-grain developer, but only at the expense of some loss of speed. Graininess is increased by overdevelopment, whether caused by high temperature extended developing time, or an overly energetic developer. Moreover, apparent graininess is increased by high density in a negative.

— Resolving Power: The resolving power of an emulsion refers to its ability to record fine detail distinguishably. The resolution of a film depends on the contrast of the test chart, but only slightly on the degree of development of the film. The resolving power classifications given in the data sheets are based upon the maximum values determined for the recommended processing. The loss of resolution with overexposure and underexposure is an important reason for exposing negatives as correctly as circumstances permit.

11.1 Black-and-White Films

The main features of some aerial black-and-white films are presented here. One should refer to the "Manual of Physical Properties of Kodak Aerial and Special Sensitized Materials" for more detailed information, such as spectral sensitivity curves, time-gamma curves, etc.

- Kodak Plus-X Aerographic Film
  2402 (Estar Base)
  Military Designation 11-33-641
  Medium-speed, high dimensional stability for mapping

  Base: 4-mil Estar polyester with fast-drying (PX) backing

  Sensitivity: Panchromatic, with extended red sensitivity
  Resolving Power: T.O.C. 1000:1 112 lines/nm (D-19)
  Resolving Power: T.O.C. 1.6:1 50 lines/mm (D-19)

  Aerial Exposure Index: 80 (Based on normal development of 8 minutes at 75°F in D-19).

- Kodak Tri-X Aerographic Film
  2403 (Estar Base)
  Military Designation 11-33-64k
  High-speed, high acutance aerial mapping film; especially suitable also for reconnaissance under minimal levels of illumination

  Base: 4-mil Estar polyester with fast-drying (PX) backing

Sensitivity: Panchromatic, with extended red sensitivity

Resolving Power: 71 lines/mm at T.O.C. 1000:1 (12 minutes, D-19)
22 lines/mm at T.O.C. 1.6:1 (12 minutes, D-19)

Aerial Exposure Index: Daylight — 250
(Based on exposure without a filter and normal development of 12 minutes at 68°F in Kodak D-19).

— Kodak Double-X Aerographic Film
2405 (Estar Base)
Military Designation 11-33-63i
Standard film for mapping and charting; high dimensional stability

Base: 4-mil Estar polyester with fast-drying (PX) backing

Sensitivity: Panchromatic, with extended red sensitivity

Resolving Power : 85 lines/mm at T.O.C. 1000:1 (DK-50)
Resolving Power: 38 lines/mm at T.O.C. 1.6: (DK-50)

Aerial Exposure Index: Daylight — 125
(Based on normal development of 8 minutes at 68°F in DK-50)

— Kodak Aerographic Duplicating Film
2420 (Estar Base)
4427 (Estar Thick Base)
Type SO-122 (Estar Thin Base)
Military Designation 2420-14-33-23d; 4427-14-35-23d
For duplicating aerial negatives; high dimensional stability, increasing with base thickness.

Base: 2420: 4-mil Estar polyester with fast-drying (PX) backing
4427: 7-mil Estar polyester with clear-gel backing
Type SO-122: 2.5-mil Estar polyester with clear-gel backing

Sensitivity: Blue-sensitive, positive materials.

Resolving Power: T.O.C. 1000:1	138 lines/mm (DK-50)
	145 lines/mm (K-76)
T.O.C. 1.6:1	84 lines/mm (DK-50)
	80 lines/mm (D-76)

— Kodak Panatomic-X Aerial Film
3400 (Estar Thin Base)
Military Designation 11-32-64q
Intermediate-speed, thin-base, high-altitude reconnaissance film

Base: 2.5-mil Estar polyester with dyed gel backing

Sensitivity: Panchromatic, with extended red sensitivity

Resolving Power: 170 lines/mm at T.O.C. 1000:1 (D-19)
Resolving Power: 65 lines/mm at T.O.C. 1.6:1 (D-19)

Aerial Exposure Index: Daylight — 20 (Based on development of 8 minutes at 68°F in D-19)

- Kodak Plus-X Aerial Film
  3401 (Estar Thin Base)
  Military Designation 11-32-64i
  Medium-speed, thin-base, high-altitude reconnaissance film

  Base: 2.5-mil Estar polyester with dyed gel backing

  Sensitivity: Panchromatic, with extended red sensitivity

  Resolving Power: 105 lines/mm at T.O.C. 1000:1 (D-19)
  Resolving Power: 40 lines/mm at T.O.C. 1.6:1 (D-19)

  Aerial Exposure Index: Daylight — 64
  (Based on normal development of 8 minutes at 68°F in D-19)

- Kodak Aerial Negative Film
  Type SO-206 (Estar Thin Base)
  Moderate speed, fine-grain film for high-altitude mapping or reconnaissance

  Base: 2.5-mil Estar polyester with dyed gel backing

  Sensitivity: Panchromatic, with extended red sensitivity

  Resolving Power: 336 lines/mm at T.O.C. 1000:1 (D-19)
  Resolving Power: 112 lines/mm at T.O.C. 1.6:1 (D-19)

  Aerial Exposure Index: Daylight — 6
  (Based on normal development of 8 minutes at 68°F in D-19)

- Kodak Direct Duplicating Aerial Film
  Type SO-239 (Estar Base)
  Very fine-grain film for one-step duplication of aerial reconnaissance negatives of high definition.

  Base: 4-mil Estar polyester with static-resistant backing

  Sensitivity: Blue-sensitive, direct-reversal material (no re-exposure necessary)

  Resolving Power: T.O.C. 1000:1 560 lines/mm
  Resolving Power: T.O.C. 1.6:1 200 lines/mm Kodak Versamat Developer 641

11.2 Color Films

Kodak Aerocolor Negative Film 2445 (Estar Base) is a high-speed, extremely fine grain, color negative areial film. This film has a wide exposure latitude. 2445 film has improved color blance and is about two f/stops faster than Kodak Ektachrome MS Aerographic Film 2448 (Estar Base) when 2448 film is processed to a color negative. The 4-mil estar base is moisture resistant and provides good flexibility, extremely good dimensional stability, and very high resistance to tear.

Kodak Aerocolor is used in low-to-medium altitude aerial mapping and aerial reconnaissance photography for such applications as geological, pollution, archaeological, crop, and forestry studies, traffic control, city planning, railway, highway, and hydraulic engineering.

The use of color-compensating filters is not necessary. A Kodak Wratten filter HF-3, or Kodak Wratten filter No. 2B, may be used to reduce the effect of atmospheric haze.

Resolving Power:

Test-Object Contrast 1000:1 — 80 lines/mm

Test-Object Contrast 1.6:1 — 40 lines/mm

RMS Granularity Value — 14 (at a net density of 1.0)

Kodak Aerial Color Film (Estar Thin Base) SO-242 and Kodak Aerial Color Film (Estar Ultra-Thin Base) SO-255 films are extremely fine-grain, slow-speed, high-definition, aerial color reversal films, and have high contrast and good color saturation to decrease the effect of atmospheric haze. The photographic properties of these two films are identical. They are designed for high-altitude, stabilized-platform aerial cameras with high-quality optical systems. These films are ideal for use in conjunction with Kodak High Definition Aerial Film 1414 (Estar Ultra-Thin Base) and Kodak High Definition Aerial Film 3414 (Estar Thin Base) in high-altitude aerial photographic systems where both color and black-and-white aerial photography may be required.

Kodak SO-255 (Estar Ultra-Thin Base) can be used in applications where maximum spool capacity is required and minimum storage space is available.

Aerial Exposure Index — Daylight (no filter) — 2
Effective Aerial Film Speed — Daylight (no filter) — 6
Resolving Power:
Test-Object Contrast 1000:1 — 200 lines/mm
Test-Object Contrast 1.6:1 — 100 lines/mm
RMS Granularity Value — 11

11.3 Reversal Color Films

Kodak Aerochrome Infrared Films 2443 and 3443 are "false color" reversal emulsions. They are designed for aerial photography and are useful for camouflage detection, agricultural and forestry work, and remote sensing applications where infrared discrimination is required. With these films, a yellow filter, such as the Kodak Wratten filter No. 12, should be used.

Kodak Aerochrome Infrared Film 2243 has a 4-mil Estar Base with a fast-drying backing. Kodak Aerochrome Infrared Film 3443 has a 2.5-mil Estar Thin Base with a clear gel backing. Both have aerial exposure indices at 10.

Kodak Ektachrome Multispectral Aerographic Film 2448 (Estar Base) is a medium-speed color reversal film used primarily for low and medium altitude mapping and reconnaissance. This film produces color transparencies which can be viewed directly or can be used for printing diapositive plates. Aerial Exposure Index — 6.

11.4 Duplicating Films

Kodak Ektachrome Aerographic Duplicating Film SO-360 is an extremely fine-grain, low-contrast, high-resolution, color reversal aerial duplicating film. This film is not intended for making original exposures in an aerial camera.

SO-360 is used to make color duplicate transparencies of Kodak Ektachrome and Aerochrome film originals from aerial surveying and reconnaissance photography.

This multilayer, color reversal film is color balanced so as to allow printing to be done by tungsten quality illumination that has a color temperature of approximately 3000°K and appropriate compensating filters.

Resolving Power:

Test-Object Contrast 1000:1 — 125 lines/mm
Test-Object Contrast 1.6:1 — 63 lines/mm
RMS Granularity — 8 (at a net density of 1.0)

CHAPTER 12

APPLICATIONS INCLUDING ISOLUMINOUS TECHNIQUES

The photographic procedures described in the foregoing chapters have dealt with the relationships between:

- image density and the associated brightness of the subject
- image color and the reflectance characteristics of the subject

The exact relationships were seen to depend upon the spectral bands photographed and the characteristic curves of both the negative and positive images. However, on conventional multispectral photography, large brightness differences in the terrain frequently prevent detection of subtle *color* differences between objects. A special process called *isoluminous photography* has been developed to eliminate this brightness problem in multispectral composite imagery.

This technique, as well as examples of multispectral photography for a variety of disciplines, is the subject of this chapter.

12.1 Isoluminous Techniques

An isoluminous multispectral composite photograph is one in which all objects in the scene are presented at the *same* brightness level. Hence, all color differences which appear on the isoluminous multispectral photograph relate to differences in the spectral distribution of the terrain. Isoluminous displays are generated from a standard set of multispectral negatives using a photographic masking process.

In order to illustrate the isoluminous procedure, a hypothetical set of characteristic curves of the blue (B), green (G), and red (R) negatives are shown in Figure 137. The x-axis represents the log intensity of the image-forming light and the y-axis the corresponding density. The gamma of the three negatives is the same and the black, gray, and white objects will, naturally, image as the same density on each negative. An object (labelled as "o" on the x-axis) which has color will exhibit a difference in the intensity of the image-forming light in each spectral band. This results in a different density in each of the three negatives denoted as D_1^O, D_2^O, and D_3^O respectively.

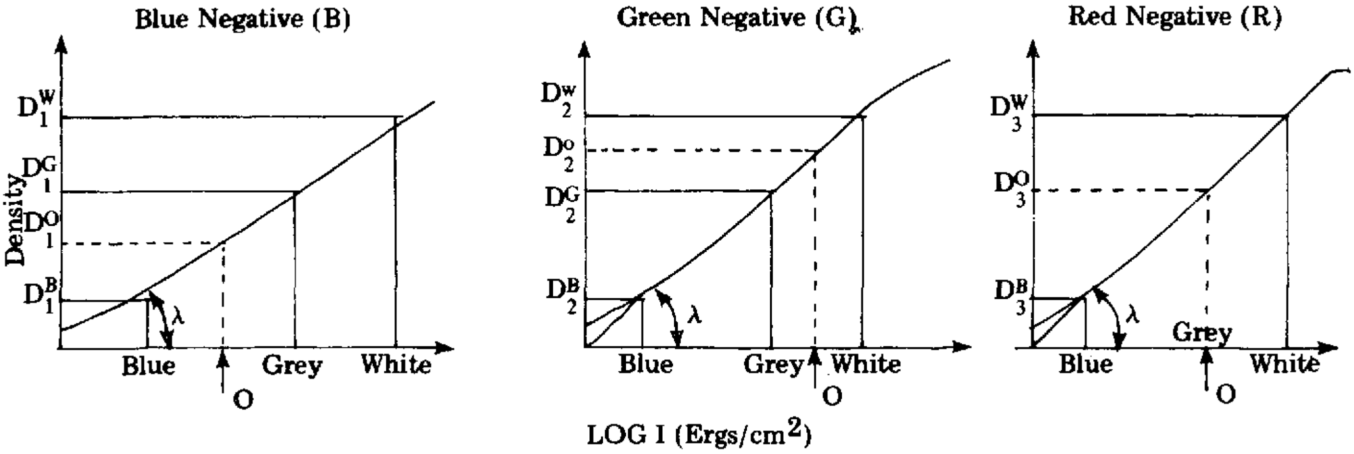


Figure 137. Characteristic Curves of the Red, Green & Blue Multispectral Negatives.

Initially, the characteristic curve of each multispectral record or band is examined and the straight line portions are defined. Two achromatic or gray areas on the imagery (one in the highlights, D max, and one in the shadows, D min) are selected for brightness normalization. That is, these areas represent the range of densities which will be reduced to a common value in the final presentation. Small circular neutral density "chips" which exactly match the D min and D max values may be reproduced along with the image in each of the processing steps. These chips will eliminate the difficulty associated with locating the exact "highlight and shadow" image areas for subsequent processing measurements. The only constraints placed upon the selection of the D min - D max areas is that both points must lie along the straight lines of the characteristic curves and the brightness ranges, Δ log E, of each set must be almost identical. This latter condition assures that the two areas are truly achromatic.

The second step of the process, shown in Figure 138, consists of producing a half gamma positive mask of each record in which the density range of the positive is only 50 percent of its corresponding negative. Verification of this desired density range is easily made by measurement of the D min - D max chips off the positive masks. The negative of each multispectral record is then registered together with the two positive masks of the other bands to form friskets of three films each, as shown in figure 139. For example:

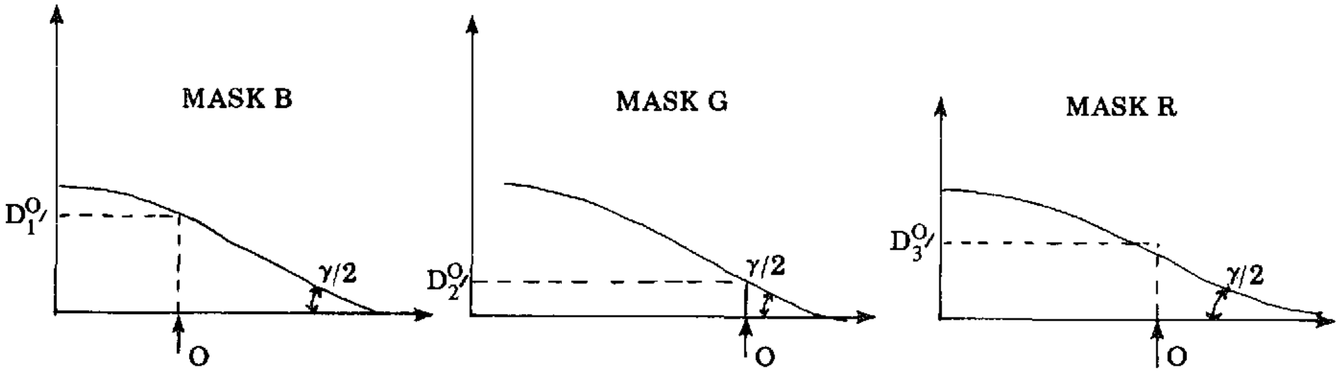


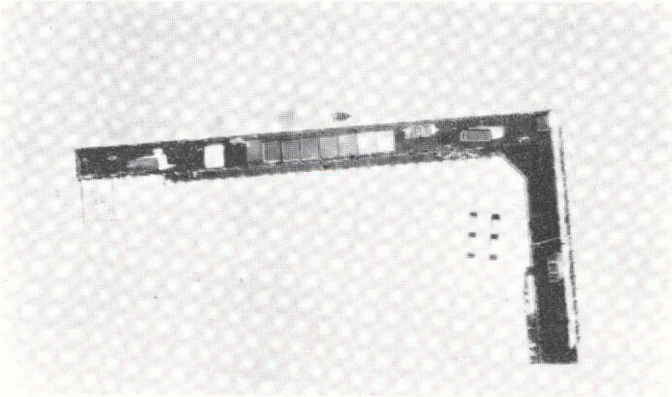
Figure 138. Characteristic Curves of Half Gamma Masks Produced from Multispectral Negatives.

Negative		Positive ½ Gamma Mask
Blue	Plus	Green and Red
Green		Blue and Red
Red		Blue and Green

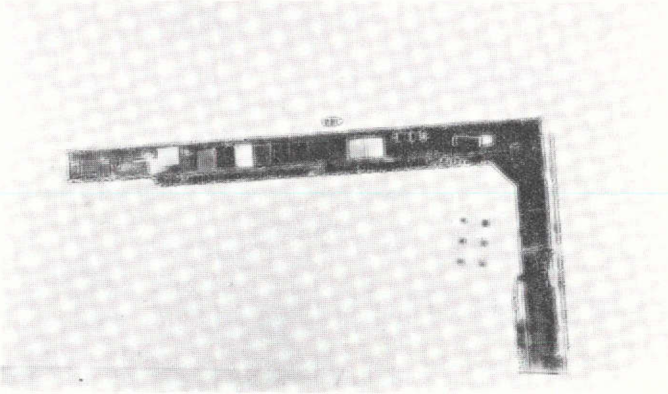
Precise exposure control is required for the accurate photometric printing of the positive masks.

The density relationships of the three negative-positive mask combinations are shown in Figure 140. The horizontal line corresponds to the linear relationship of the brightness for any colorless object lying on the straight line portion of the characteristic curve. The density of object "o", however, is different on all three masked positives. When projected in an additive color viewer with the masked blue positive projected as red, the image shown in Plate Xc results. Note that the gray scale on the dock has a uniform gray level. The sub-surface gray scale target is a uniform green color because of the transmission characteristics of the water mass. The colored objects maintain their vivid hue.

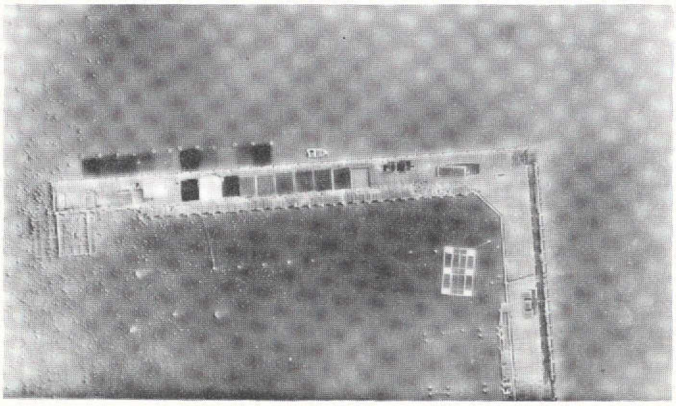
If neutral chips have been masked along with the imagery, they will have the same density values indicating that the D max - D min brightness differences have truly been eliminated from the photo.



Frisket consisting of
Blue M-S record &
half gamma mask of
green & red records.



Frisket consisting of
Green M-S record
& half gamma masks
of blue & red records.



Frisket consisting of
Red M-S record &
half gamma masks
of blue & green records.

Figure 139. Positive friskets which were additively projected as blue, green and red respectively to produce color plate Xc.

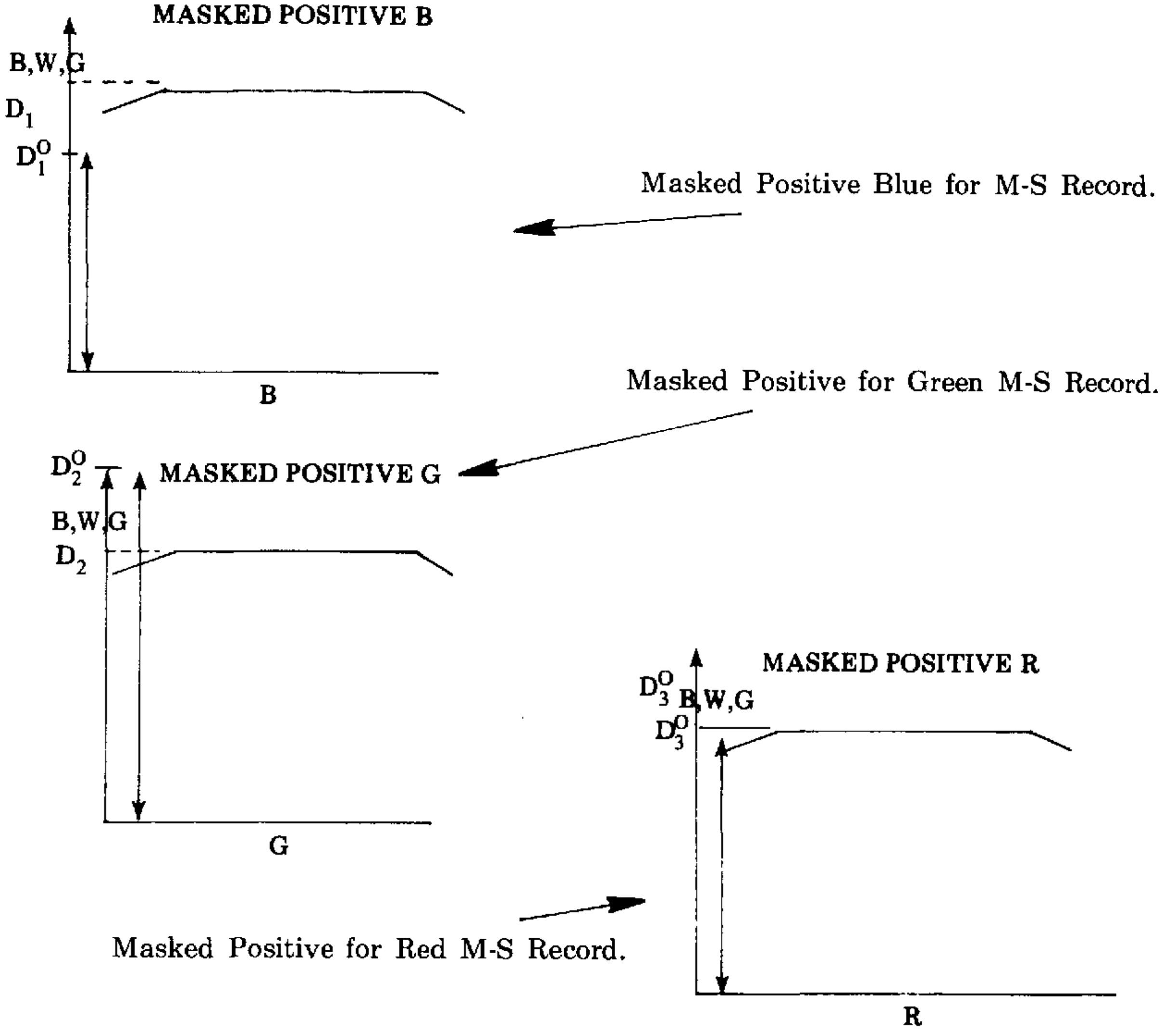


Figure 140. Characteristic curves of negative half-gamma positive mask combination.

12.2 Applications

This section presents several examples of the multispectral photographic techniques for a variety of user applications. Reference will be made to the color plates which are in the center of this text. No spectral reflectance curves have been given because the distributions of terrain objects change as a function of the environmental conditions and site location. The reader is referred to Chapter 7. for a thorough discussion of both spectra acquisition and data reduction.

Test Site Description

BARATARIA BAY, Louisiana. This area just east of Milligan Point possesses a variety of marsh grasses. The water is extremely turbid due to the shallow depths and the dredging operations which are constantly underway to keep the waterway open. Strong winds from the Gulf of Mexico cause a good deal of wave action in the area.

Targets to be Detected

- Spartina alternaflora
- Black mangrove
- Distilus spicata

Flight Information

Date:	12 April 1969
Time:	1340 EST
Altitude:	4,500 feet
Weather:	Cloudy
Film:	EK #8403
Filters:	Red, blue, deep red, green

Processing — Negative

Record	1	2	3	4
Gamma	2.6	2.0	3.0	2.3
Minimum Density	.19	.22	.21	.20

Processing — Positive

Record	1	2	3	4
Gamma	2.5	2.1	2.6	2.0
Minimum Density	.29	.28	.34	.32

Ground Truth — See figure 141c

1 - Spartina alternaflora dieback
2 - Spartina alternaflora
3 - Distichlis spicata
4 - Black mangrove

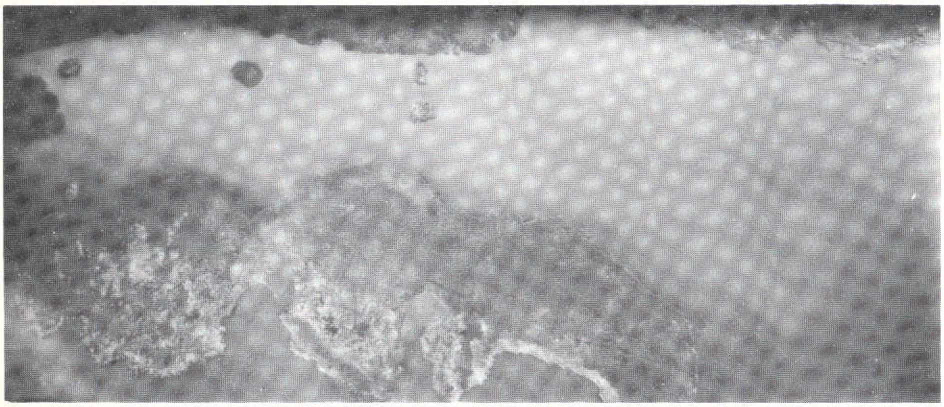


Figure 141a

Spectral Band - Red
Peak Wavelength - 700 nm
Peak Transmission - 91%
½ Bandpass - 130 nm
f/Number - 4 +.4 ND

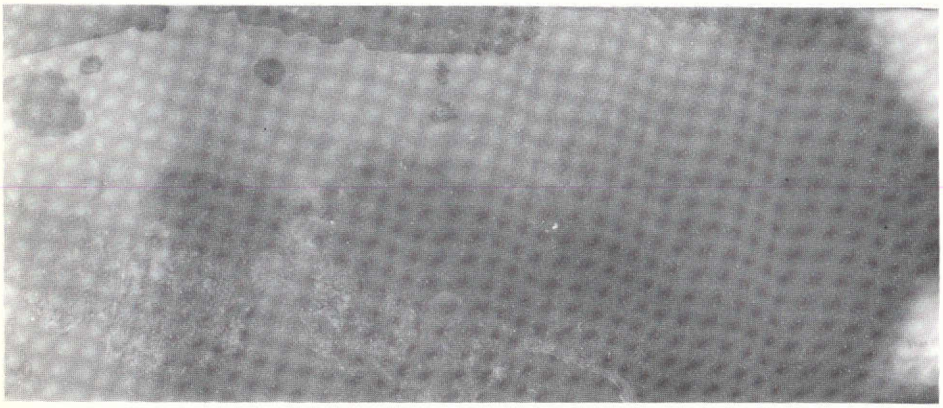


Figure 141b

Spectral Band - Blue
Peak Wavelength - 430 nm
Peak Transmission - 40%
½ Bandpass - 55 nm
f/Number - 4

Analysis of Black and White Positives

-- The first record, namely red, was selected for its ability to speciate the various types of marshland vegetation. The Spartina alternaflora, labelled as 1 and 2 on the ground truth, can be readily detected on this record due to its texture. The lush alternaflora, labelled 2, along the water's edge and in the middle of the marsh region is differentiated from the alternaflora labelled 1 which is a dieback. Black mangrove, although not shown in the multispectral color composite of Plate IVa, is quite apparent in this record. The Distichlis spicata can readily be seen as a low density area in the red record. The blue spectral band is of little use in differentiating between marshland species. This can be seen by comparing the density of the Spartina alternaflora with the black mangrove area. This blue record was somewhat overexposed in order to preserve the ground detail contained in it. Record #3, which is a deep red spectral band, is as useful as Record #1 for typing marshland vegetation. Although the water areas appear to be somewhat overexposed, one should note that the density of area 2 is approximately the same as that of the first record. The fourth multispectral band, light green, shows no apparent difference in the areas labelled 1 and 2 (Spartina alternaflora). The processing was such that the density of area 2 is approximately the same as that of Records #1 and #3.

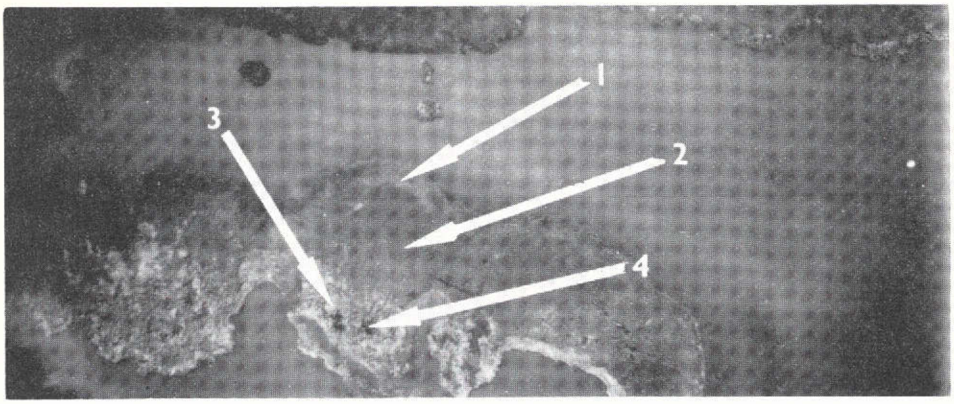


Figure 141c

Spectral Band - Deep Red
Peak Wavelength - 700 nm
Peak Transmission - 79%
½ Bandpass - 60 nm
f/Number - 4

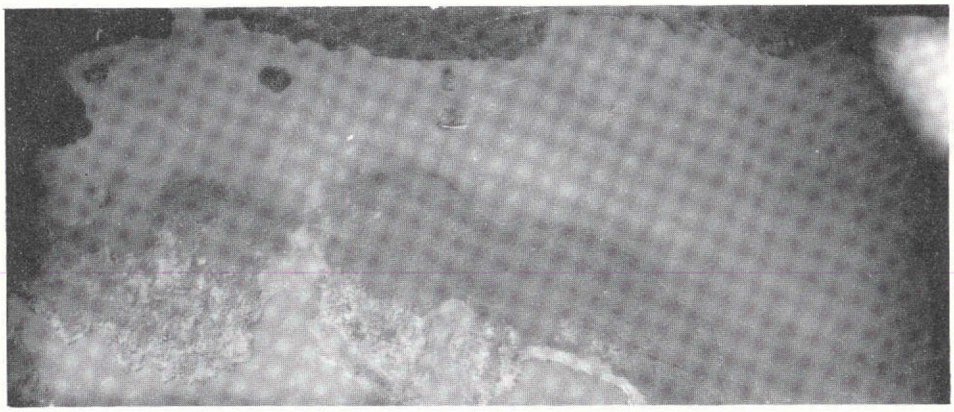


Figure 141d

Spectral Band - Light green
Peak Wavelength - 515 nm
Peak Transmission - 52%
½ Bandpass - 42 nm
f/Number - 4

Viewing Filters

Record	1	2	3	4
Filter	Red	Blue	—	Green
Saturation Level	65%	90%	—	60%

Evaluation of Multispectral Color Composite

— The multispectral color rendition shown in Plate VIa was reproduced by the additive combination of Records #1, #2, and #4 projected as red, blue, and green respectively. The dieback along the shore, as well as the less lush alternaflora, is produced here as a desaturated cyan color, while the more vigorous alternaflora is presented as a magenta color. In the lower portion of Plate VIa the Distichlis spicata is shown as an achromatic shade. Such color combinations result from balancing the brightness of each projection system. That is, the brightness of Records #1 and #3 were decreased substantially, while the brightness through Record #2, projected as blue, was increased considerably. This particular rendition was useful in the rapid assessment of the vigor of alternaflora.

APPLICATION — ESTUARINE ECOLOGY

Test Site Description

MISSISSIPPI RIVER DELTA. The area between Sawdust Bayou and South Pass possesses extremely turbid water. Plankton blooms from the upland marshes flow into the estuarian system in great profusion.

Targets to be Detected

- Plankton bloom
- Turbidity dispersion

Flight Information

Date:	12 April 1969
Time:	1334 EST
Altitude:	4,500 feet
Weather:	Cloudy
Film:	EK #8403
Filters:	Red, blue, deep red, green

Processing — Negative

Record	1	2	3	4
Gamma	2.6	2.0	3.0	2.3
Minimum Density	.19	.22	.21	.20

Processing - Positive

Record	1	2	3	4
Gamma	2.5	1.6	2.3	1.8
Minimum Density	.13	.24	.13	.22

Ground Truth - See figure 142d

1 - Phytoplankton outpouring
2 - Area without water turbidity
3 - Phytoplankton dispersion

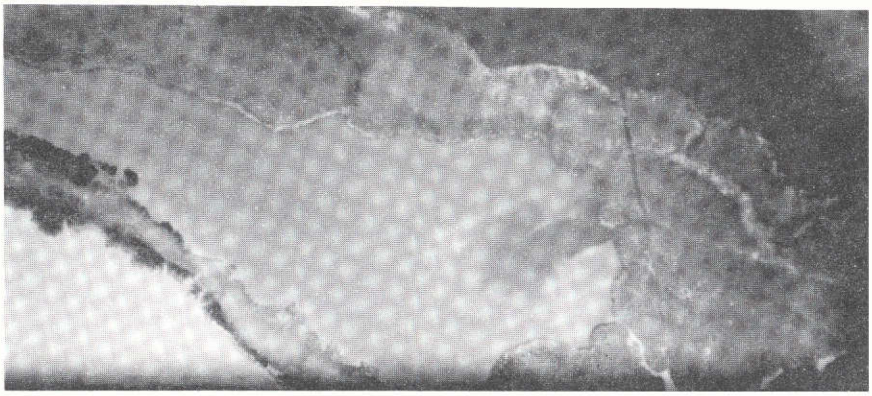


Figure 142a

Spectral Band - Red
Peak Wavelength - 700 nm
Peak Transmission - 91%
½ Bandpass - 130 nm
f/Number - 4 + .4 ND

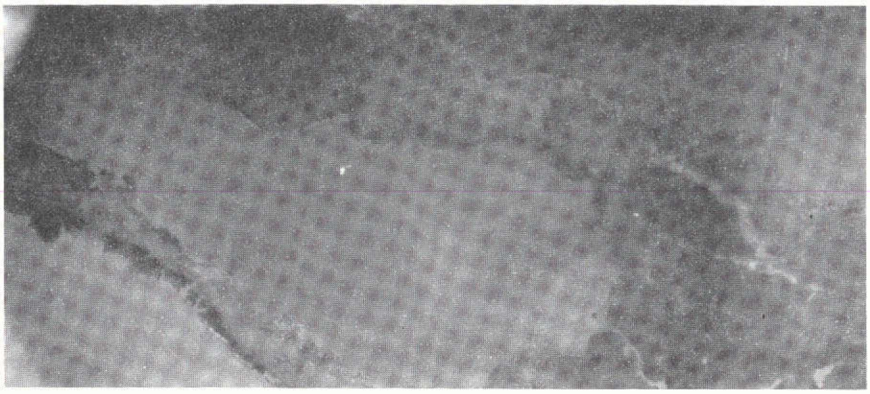


Figure 142b

Spectral Band - Blue
Peak Wavelength - 430 nm
Peak Transmission - 40%
½ Bandpass - 55 nm
f/Number - 4

Analysis of Black and White Positives

— The presence of turbidity in the form of a phytoplankton bloom along the Mississippi River Delta is most obvious on the red spectral record. The minimum density is low and the contrast is excellent. Also clearly visible in this band are differences in vegetation species, including diebacks along the shoreline in alternaflora and black mangrove on the left portion of the photograph. The blue spectral region is low in brightness level and has poor contrast.

It was necessary to overexpose this positive record in order to enhance the presence of the planktom bloom. The deep red spectral band lacks the contrast of the first record for the land areas; this particular set of processing conditions was selected to enhance the water area and, in particular, the turbidity. The diffusion of the phytoplankton into the surrounding water mass is not nearly as apparent on this third record as it was in the first. The light green band has been overexposed as was the blue in order to increase the visibility of the phytoplankton outpouring and also to show the diffusion pattern of the plankton into the surrounding water mass. Less exposure caused the diffusion pattern to blend with the surrounding water.

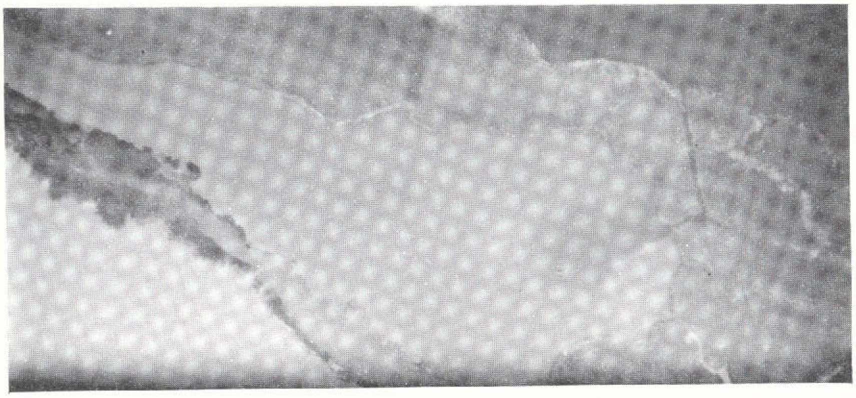


Figure 142c

Spectral Band - Deep Red
Peak Wavelength - 700 nm
Peak Transmission - 79%
½ Bandpass - 60 nm
f/number - 4

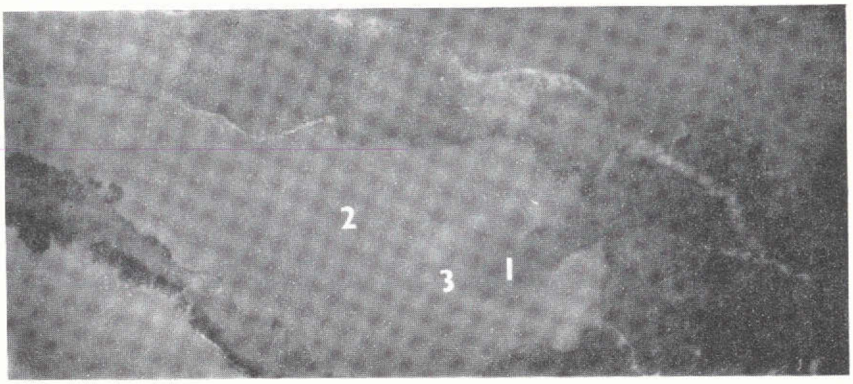


Figure 142d

Spectral Band - Light green
Peak Wavelength - 515 nm
Peak Transmission - 52%
½ Bandpass - 42 nm
f/Number - 4

Viewing Filters

Record	1	2	3	4
Filter	Blue	—	Red	Green
Saturation Level	90%	—	85%	100%

Evaluation of Multispectral Color Composite

— The multispectral rendition shown in Plate VIb was generated by projecting Records #1,#3, and #4 as blue, red, and green respectively. The phytoplankton bloom itself is most obvious in the combined projection of Records #1 and #4. The reader should note the small changes in hue just above the plankton outpouring; small differences in density caused by some unknown turbidity apparent on Records #3 and #4 become visible as a yellow hue. It is interesting to note here that the diffusion of the plankton into the surrounding water mass is not as obvious on the color rendition as it was on the black-and-white. This is due to the saturation balance in the multispectral viewer which was set in order to maximize the presence of the bloom itself.

APPLICATION – POLLUTION MONITORING

Test Site Description

Laurel Bay, South Carolina. This test site is on the Broad River near the Laruel Bay Naval housing area. The effluent from a sewage treatment plant located at Laurel Bay Village invades the small tributaries on its path to the river.

Targets to be Detected

– Pollution detection in river near sewage treatment plant.

Flight Information

Date:	15 July 1971
Time:	1010 EST
Altitude:	7,800 feet
Weather:	Clear
Film:	EK # 2424
Filters:	Light green, yellow, orange, infrared

Processing – Negative

Record	1	2	3	4
Gamma	1.2	1.1	1.6	1.5
Minimum Density	.5	.38	.27	.35

Processing – Positive

Record	1	2	3	4
Gamma	2.2	2.0	2.2	2.1
Minimum Density	.45	.40	.31	.37

Ground Truth – See Figure 143a

1 – Effluent from sewage treatment plant in small stream
2 – Uncontaminated stream
3 – Effluent outpouring into Broad River

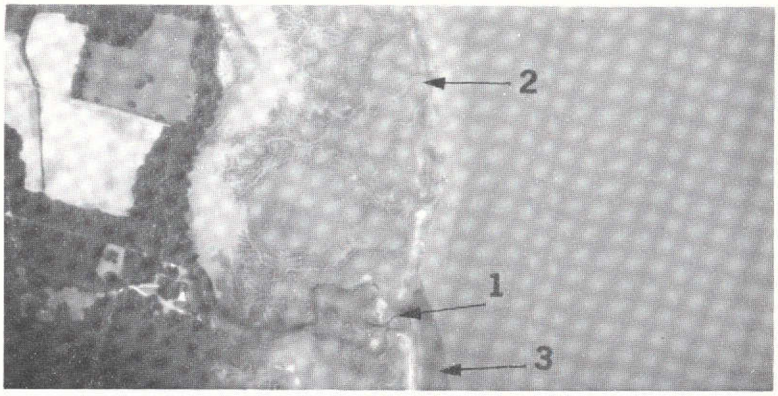


Figure 143a

Spectral Band — Light Green
Peak Wavelength — 520 nm
Peak Transmission — 80%
½ Bandpass — 62 nm
f/Number — 4

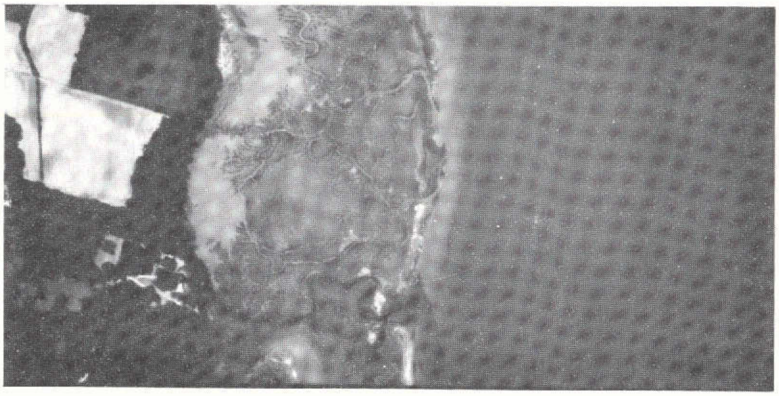


Figure 143b

Spectral Band — Yellow
Peak Wavelength — 620 nm
Peak Transmission — 80%
½ Bandpass — 50 nm
f/Number — 8

Analysis of Black-and-White Positives

— The first record (light green spectral band) shows good discrimination between area 1 which is the effluent from the Laurel Bay Village sewage treatment plant and area 2 which is an uncontaminated stream approximately 150 yards upstream. This record was exposed and processed in order to maximize the density differences within the marsh. The presence of effluent outpouring into Broad River in area 3 is also clearly apparent. Record # 2 (yellow) also shows good discrimination between the contaminated and uncontaminated streams and waters. The positive exposure and processing were again selected in order to maximize differences in the marshland areas; hence, all detail in the deciduous foliage on the left portion of the photograph is lost. Record #3 (orange band) shows excellent detail in the heavy deciduous foliage to the left of the photograph and it is also helpful in discriminating between marsh vegetation types. However, this band is relatively useless in differentiating between the contaminated and uncontaminated stream. The high gamma in this record, as well as the reflectance characteristics of the effluent, make its outpouring into Broad River invisible in this band. The fourth spectral record, the near-infrared, also shows no differentiation between the streams labelled 1 and 2. Again, the absorption characteristics of the water mass in this band do not permit any differentiation between the effluent outpouring and the background waters of Broad River. Positive exposure is reasonably heavy in order to enhance detail in the marshland areas.

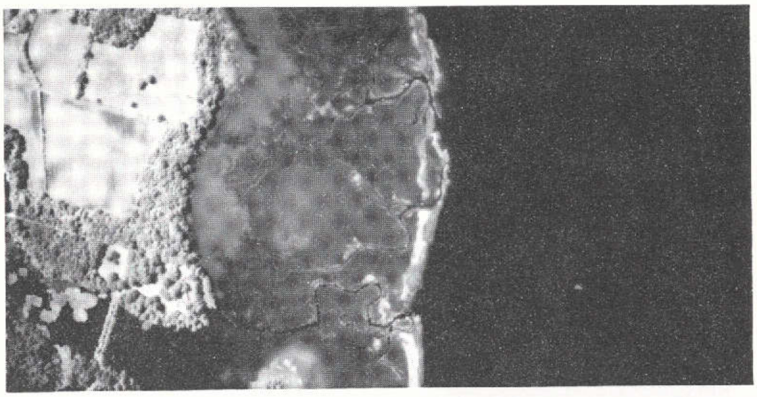


Figure 143c

Spectral Band — Orange
Peak Wavelength — 723 nm
Peak Transmission — 86%
½ Bandpass — 35 nm
f/Number — 6.3

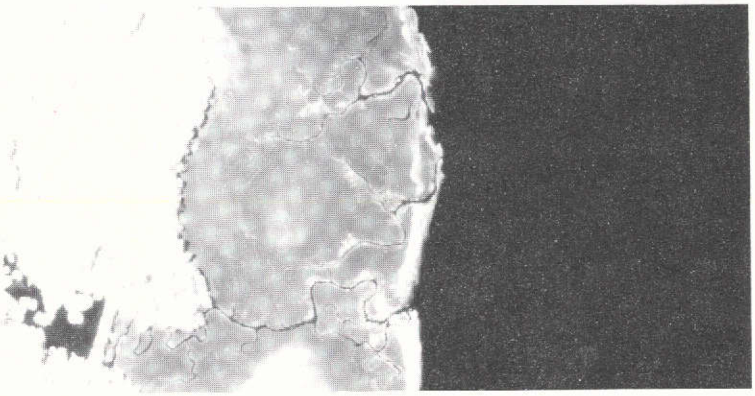


Figure 143d

Spectral Band — Near infrared
Peak Wavelength — 860 nm
Peak Transmission — 60%
½ Bandpass — 120 nm
f/Number — 9.4

Viewing Filters

Record	1	2	3	4
Filter	Blue	Red	Green	—
Saturation Level	90%	95%	25%	—

Evaluation of Multispectral Color Composite

— The multispectral color presentation shown in Plate VIc was generated by a recombination of Records #1, #2, and #3 as blue, red, and green respectively. The presence of uncontaminated waters in the upper stream, best seen in Records #1 and #2, causes the characteristic magenta color. Also, the low density of the water in these two records results in the off-shore river area being a saturated deep magenta. The stream which has been polluted by the sewage treatment plant effluent is naturally rendered black because of the high density characteristics of this area on each of the positive multispectral records. The only real contribution of Record #3 is to make vivid the lush vegetation which lies on the left portion of the photograph and to enhance some of the marshland growth between the contaminated and the uncontaminated streams.

Test Site Description

CALLAWASSIE ISLAND, South Carolina. This region is located off the Colleton River, due west of Port Royal Sound. It contains a large number of vegetation species in its extensive marshlands. Tidal inundation is nominally 4.5 feet twice a day, the barren mud flats being exposed at the ebb.

Targets to be Detected

- Distichlis sp.
- Typha sp.
- Juncus roemerianus
- Salicornia bigelovii
- Spartina alternaflora (less than 2 ft. high)
- Spartina alternaflora (very lush)
- Barren mud flats

Flight Information

Date:	15 July 1971
Time:	1000 EST
Altitude:	7,800 feet
Weather:	Clear
Film:	EK #2424
Filters:	Light green, yellow, orange, infrared

Processing — Negative

Record	1	2	3	4
Gamma	1.2	1.1	1.6	1.5
Minimum Density	.5	.38	.27	.35

Processing — Positive

Record	1	2	3	4
Gamma	2.2	2.0	2.2	2.1
Minimum Density	.45	.40	.31	.37

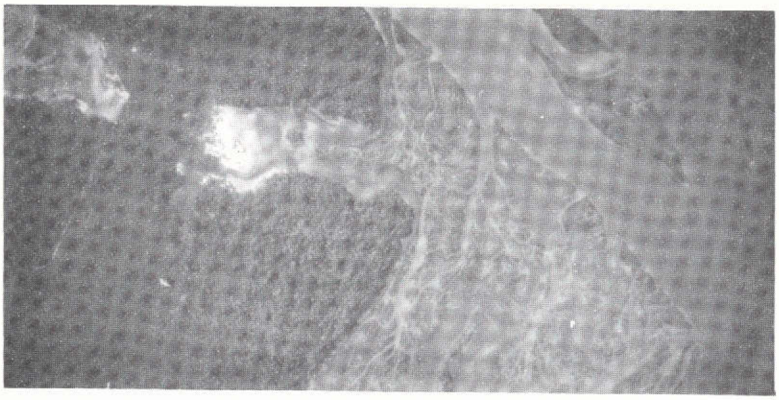


Figure 144a

Spectral Band — Light green
Peak Wavelength - 520 nmn
Peak Transmission — 80%
½ Bandpass — 62 nm
f/Number — 4

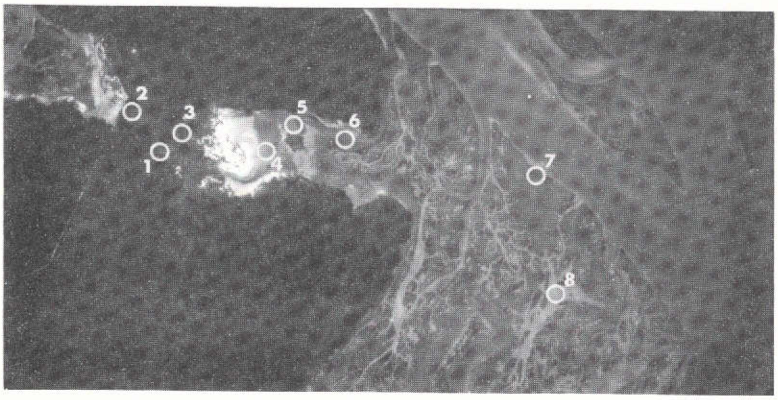


Figure 144b

Spectral Band — Yellow
Peak Wavelength — 620 nm
Peak Transmission — 80%
½ Bandpass — 50 nm
f/Number — 8

Ground Truth — See figure 144b

1 - Distichlis spicata
2 - Typha sp.
3 - Juncus roemerianus
4 - Salicornia bigelovii
5 - Spartina alternaflora
6 - Spartina alternaflora (less than 2 feet high)
7 - Spartina alternaflora (very lush)
8 - Barren mud flat

Analysis of Black-and-White Positives

— The first multispectral record (light green) has been printed and processed not only for enhancement of the marshland areas, but also to maintain the detail in the upland vegetation. Processing to a higher gamma resulted in the areas labelled 1, 2, and 3 being on the shoulder of the characteristic curve. A decrease in exposure in order to reduce the density of the barren area between 3 and 4 resulted in a loss of detail in the marsh. The second spectral band (yellow) has been printed

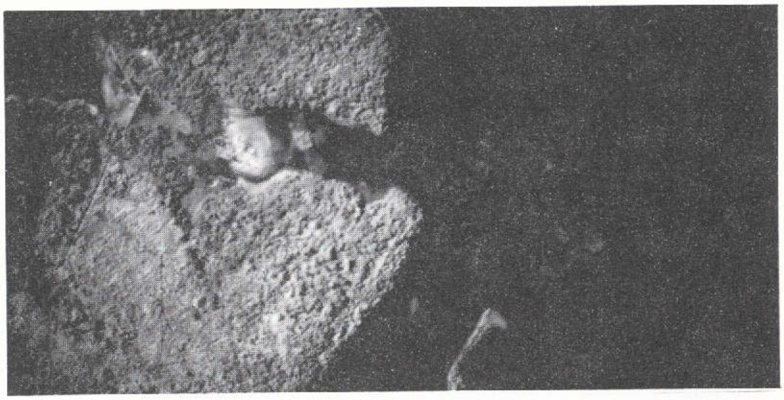


Figure 144c

Spectral Band — Orange
Peak Wavelength — 723 nm
Peak Transmission — 86%
½ Bandpass — 35 nm
f/Number — 6.3

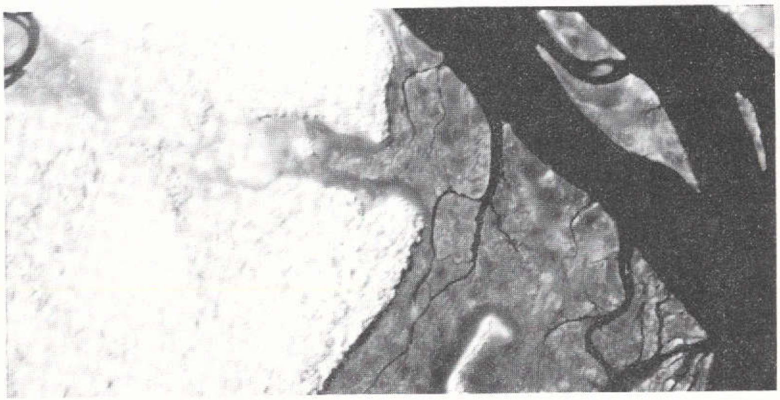


Figure 144d

Spectral Band — Near infrared
Peak Wavelength — 860 nm
Peak Transmission — 60%
½ Bandpass — 120 nm
f/Number — 9.4

and processed in order to maximize the differences between the marshland species without regard for the upland vegetation towards the left. Discrimination between areas labelled 7 and 8 is quite good, while no discrimination is apparent between 2, 5, and 6. Record #3 (orange) has been printed and exposed in order to maximize the detail of the marshes between regions marked 1 and 6. Differences between areas5 and 6 which were invisible on the second record are now present. The reflectance between areas 7 and 8 is exactly opposite of what it was for band #2, i.e., area 7 has a higher reflectance than area 8 in the orange region. One should also note that the extreme detail surrounding area 8 which was present in the yellow spectral band is missing in the orange. The fourth record, near-infrared, was processed also for the marshland areas; hence, all detail in the decidous foliage lying on the left portion of the photograph is lost. No detail exists in areas marked 1, 2 and 3 since the exposure placed these areas on the toe portion of the characteristic curve. Exposing this particular record for the left-hand portion of the photograph rendered the marshland area a uniform gray.

Viewing Filters

Record	1	2	3	4
Filter	Blue	Green	—	Red
Saturation Level	100%	90%	—	100%

— The additive recombination of Records #1, #2, and #4 projected as blue, green, and red respectively results in the composite image shown in Plate VId. Area 4 is seen as a grayish-tan color, area 5 is a brown-gray, area 6 is a blue-purple, area 7 is an orange, and area 8 is seen as a desaturated blue. It is unfortunate that the three regions marked 1, 2, and 3 have not been imaged in this particular rendition. Nevertheless, each of the other species of marshland vegetation can be uniquely categorized according to its particular color. Record # 3 was not used in this rendition because of its extremely low brightness level and the small density differences which exist in the marsh region of the photo.

Test Site Description

HULL ISLAND, MASSACHUSETTS lies along south Boston Harbor, east of Dorchester Bay. The area is surrounded by stony beaches and an underwater terrain which varies in depths between 2 and 31 feet. The currents run at approximately 1.5 knots along the northern shore.

Targets to be Detected

— Subsurface terrain features.

Flight Information

Date:	8 October 1971
Time:	0900 EDT
Altitude:	18,000 feet
Weather:	Clear
Film:	EK #2424
Filters:	Blue, green, orange, deep red

Processing — Negative

Record	1	2	3	4
Gamma	2.3	1.98	1.78	1.3
Minimum Density	.41	.37	.44	.62

Processing — Positive

Record	1	2	3	4
Gamma	2.3	2.1	2.0	1.9
Minimum Density	.25	.21	.22	.30

Ground Truth — See figure 145b

A - 1-4 feet at mean low tide
B - Beach area
C - 5-10 feet at mean low tide
R - Rocks

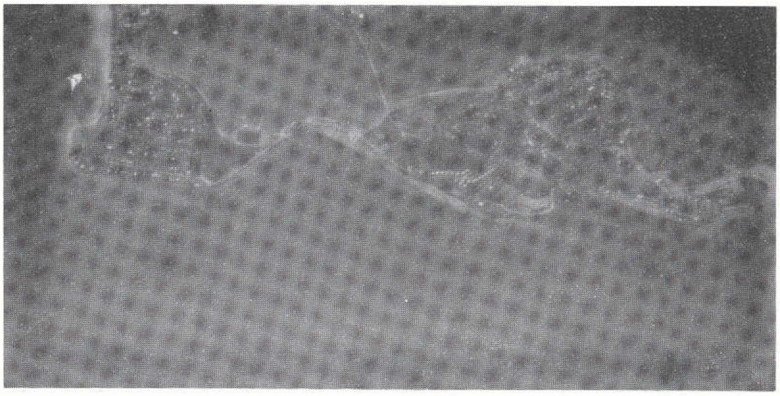


Figure 145a

Spectral Band — Blue
Peak Wavelength — 440 nm
Peak Transmission — 80%
½ Bandpass — 65 nm
f/Number — 8

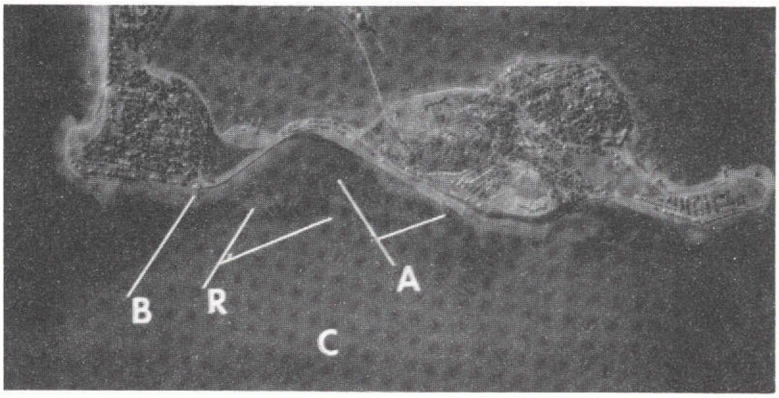


Figure 145b

Spectral Band — green
Peak Wavelength — 553 nm
Peak Transmission — 78%
½ Bandpass — 60 nm
f/Number — 5.6

Analysis of Black-and-White Positives

— The first multispectral record, exposed through a broad band blue filter, shows no shoreline detail. Each of the four multispectral bands have been exposed, printed, and processed in order to enhance underwater and shoreline details. The lack of contrast in the land areas (for Record #1) is due to the fact that the imagery was exposed only for sub-surface features. Record #2 (green) shows excellent underwater detail, particularly in the lower portion of the photograph. Beachline areas appear to be as dense as the rock, primarily because the tide was in a mid-position and the water covering both the B and R areas was approximately the same. The area labelled A lies between two and four feet of water and can clearly be differentiated from the rock and beach, as well as the deeper water at C. The positive was printed quite heavily in order to place the shadows on the straight line of the H & D curve. The third spectral region (orange) also shows good underwater detail out to a depth of approximately eight feet. Detail in the highlighted areas is also improved over the green and indicates that this record is probably the one most valuable for a compromise photograph between highlights and shadows. The fourth multispectral record (deep red) is not nearly as valuable for sub-surface terrain features as Records #2 and #3. Detail in the land areas is vastly improved over the other three, with the high reflectance characteristics of the sandy shoreline being most obvious in Records #3 and #4.

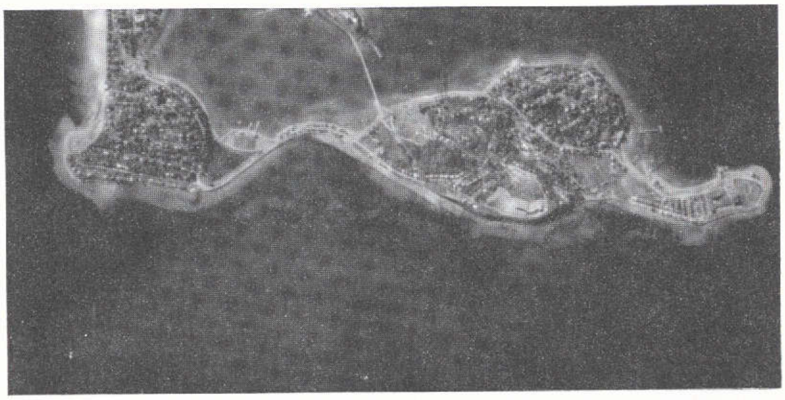


Figure 145c

Spectral Band — Orange
Peak Wavelength — 620 nm
Peak Transmission — 80%
½ Bandpass — 62 nm
f/Number — 8

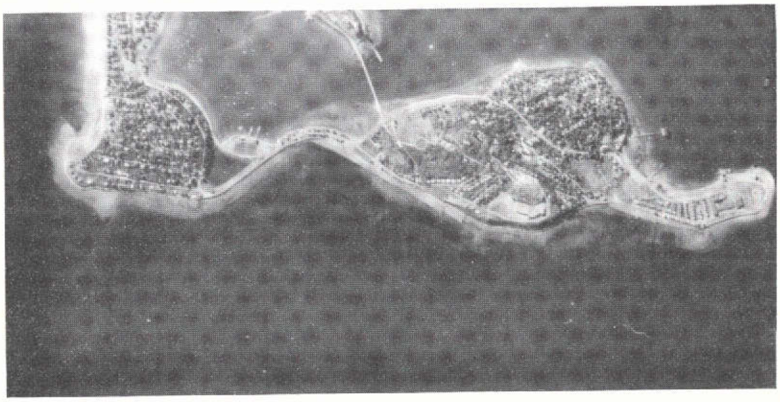


Figure 145d

Spectral Band — Deep Red
Peak Wavelength — 683 nm
Peak Transmission — 80%
½ Bandpass — 31 nm
f/Number — 4

Viewing Filters

Record	1	2	3	4
Filter	—	Blue	Green	Red
Saturation Level	—	100%	50%	80%

Evaluation of Multispectral Color Composite

— The additive recombination of Records #2, #3, and #4 projected as blue, green, and red respectively result in the additive combination seen in Plate VIe. The highlighted areas are extremely desaturated in order to increase the detail of the off-shore area and the small differences in sub-surface terrain brightness. The beachland areas in this rendition are seen as pink; water which lies at a depth of between two and four feet is a deep blue. Submerged rocks are a pinkish-blue hue, while the open water tends to a desaturated blue. The shallow waters are a darker blue than the open waters because in the case of the former we are actually looking at the sub-surface terrain. A small amount of reflection from the open water surface has decreased the density of area C in the positive records. The consequence of this is that the blue hue associated with the greater depth is considerably more desaturated in the final multispectral rendition.

APPLICATION — HYDROLOGY

Test Site Description

DEER ISLAND LIGHT, MASSACHUSETTS lies in the center of President Roads in Boston Harbor. A sewage dump exists just east of the light where the water is about 50 feet deep. This main entrance to Boston Harbor is well channeled with currents running between 1.3 and 1.7 knots.

Targets to be Detected

— Salt/fresh water interface.

Flight Information

Date:	8 October 1971
Time:	1310 EDT
Altitude:	9,000 feet
Weather:	Cloudy
Film:	EK #2424
Filters:	Blue, deep red, infrared, infrared

Processing — Negative

Record	1	2	3	4
Gamma	2.3	1.98	1.78	1.3
Minimum Density	.41	.37	.44	.62

Processing — Positive

Record	1	2	3	4
Gamma	2.3	2.1	3	4
Minimum Density	.25	.21	.22	.30

Ground Truth — See figure 146b

1 - Fresh water flow
2 - Salt water

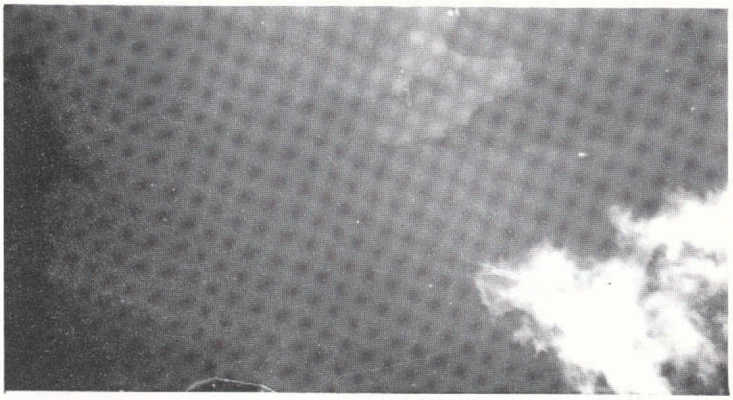


Figure 146a

Spectral Band — Blue
Peak Wavelength — 440 nm
Peak Transmission — 80%
½ Bandpass — 65 nm
f/Number — 5.6

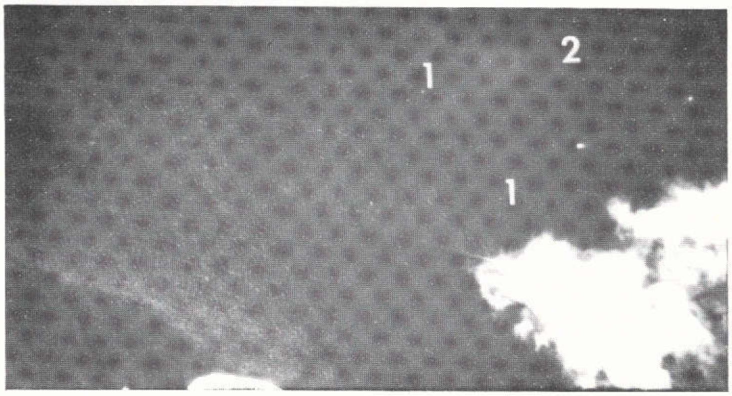


Figure 146b

Spectral Band — Deep Red
Peak Wavelength — 683 nm
Peak Transmission — 80%
½ Bandpass — 31 nm
f/Number — 2.8

Analysis of Black-and-White Positives

— The presence of a fresh/salt water interface off Deer Island in the Boston Harbor area is most apparent using a broad band blue filter. Although the blue record appears to be very low in brightness, any exposure less than that shown resulted in a "wash-out" of the distinct line between the fresh and salt water. The deep red spectral band has been purposely exposed only for the watered areas. In the lower-most portion of the photograph, one can see the tip of Long Island Head in which the beach areas containing bluffs and heavily wooded regions are completely washed out. The presence of the fresh water bloom is not nearly as apparent in the deep red as it was in the blue. The near-infrared band was exposed in a multispectral camera in the hope that the difference between the biological growth contained in the fresh and the salt water would be maximized; however, this record proved to be useless for this purpose. Equally poor is the near-infrared record whose peak transmission is 860 nanometers. Alterations in both exposure time and processing conditions failed to enhance the interface here.

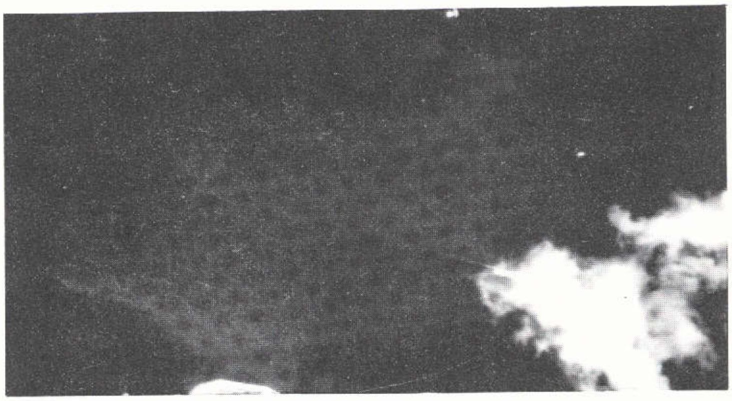


Figure 146c

Spectral Band — Near infrared
Peak Wavelength — 723 nm
Peak Transmission — 80%
½ Bandpass — 35 nm
f/Number — 2.8

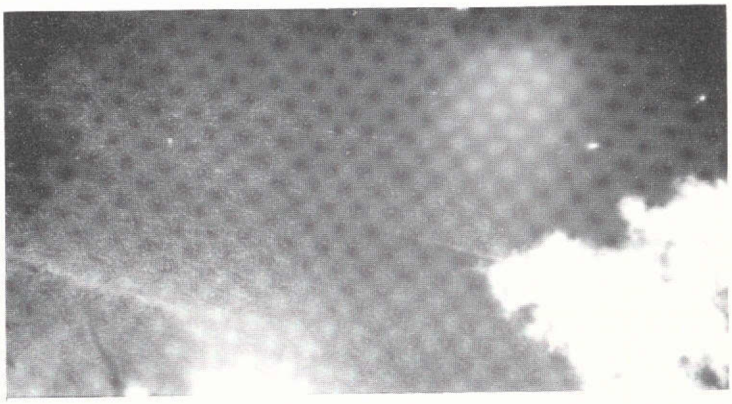


Figure 146d

Spectral Band — Near infrared
Peak Wavelength — 860 nm
Peak Transmission — 60%
½ Bandpass — 120 nm
f/Number — 2.8

Viewing Filters:

Record	1	2	3	4
Filter	Red	Green	Blue	—
Saturation Level	90%	90%	70%	—

Evaluation of Multispectral Color Composite

— Plate VIf has been rotated 90° in a counter-clockwise direction from the black-and-white positives shown in Figure 146a through 146d. The particular additive presentation in Plate VIf resulted from the recombination of Records #1, #2, and #3 projected as red, green, and blue respectively. These blooms were only visible in Records #1 and #2 with the addition of red and green yielding a yellow bloom. Record #3 was added strictly for balancing purposes; in the final rendition of Plate VIf the salt water can be seen as an orange, while the relatively fresh water is a greenish-yellow. The primary reason for the inclusion of Record # 3 was to render the cloud as a pure white in order to differentiate it from the bloom itself. Had Record #3 been excluded, this clouded area would have appeared as a very bright yellow leading an interpreter perhaps to falsely believe that it could be an extension of the interface.

APPLICATION – GEOLOGY

Test Site Description

GUNNISON HILLS between Willcox and Tucson, Arizona, has a gentle slope of about 10 degrees, although isolated peaks do exist. Variations in terrain brightness caused by the relief patterns is clearly evident when overflying the region. It is sparsely covered with vegetation.

Targets to be Detected

- Alluvium
- Shale
- Dolomite
- Limestone

Flight Information

Date:	9 March 1969
Time:	1150 MST
Altitude:	10,000 feet
Weather:	Cloudy
Film:	EK #2424
Filters:	Blue, Green, Red, Infrared

Processing – Negative

Record	1	2	3	4
Gamma	.8	.93	.93	.85
Minimum Density	.5	.4	.38	.35

Processing – Positive

Record	1	2	3	4
Gamma	1.61	1.7	1.76	1.7
Minimum Density	.52	.44	.4	.39

Ground Truth – See Figure 147a

L,S	– limestone and abundant thin beds of shale
A	– alluvium
L, D	– limestone, dolomite

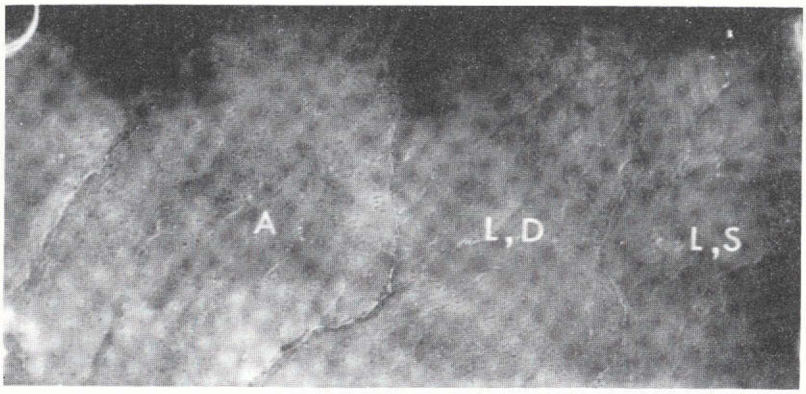
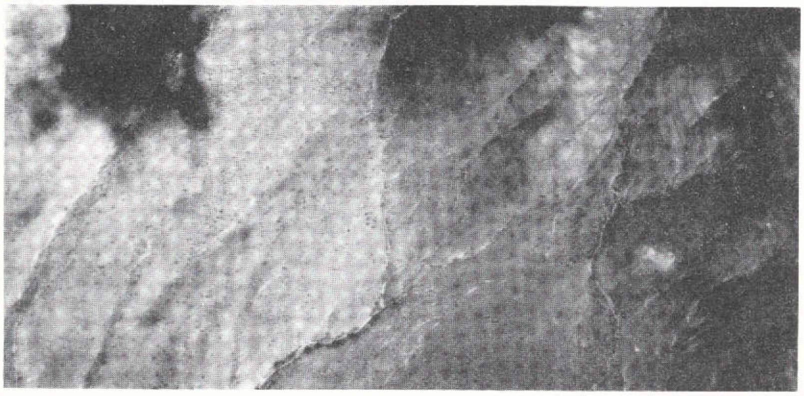


Figure 147a

Spectral Band — Blue
Peak Wavelength — 440 nm
Peak Transmission — 50%
½ Bandpass — 73 nm
f/Number — 16



147b

Spectral Band — Green
Peak Wavelength — 530 nm
Peak Transmission — 54%
½ Bandpass — 67 nm
f/Number — 5.6

Analysis of Black-and-White Positives

— The first spectral record (blue) possesses a rather low, but uniform, reflectance in the blue spectral region. The dark areas at the upper portion of the photograph are shadows of clouds. This multispectral record required more exposure in the positive printing than the other three in order to preserve the small amount of detail that was present in the negative. The second multispectral record was exposed through a green filter and the area labelled A is distinctly brighter than that labelled L, D, or S. The dark region on the right portion of the photograph is due to shadow caused by the sloping terrain. The region on the right portion of the photograph is approximately 500 feet higher than that on the left, and the white area on the right is a small peak. In the third multispectral record (red), the regions marked A, L, and D are nominally the same brightness, although a darker band does exist in the A region. Again, the effect of shadow on the extreme right-hand side of the photograph can be seen. The fourth multispectral record (near-infrared) has approximately the same spectral characteristics as the red region, although the presence of the shadow on the right-hand portion of the photograph is much more pronounced. In general, these four multispectral records were somewhat difficult to process because of the extreme differences in brightness which existed across the image. Much of the higher reflecting alluvium and limestone fell along the toe portion of the characteristic curve, especially in Records # 3 and #4, while the extreme right-hand portion of the photograph existed primarily along the shoulder portion.

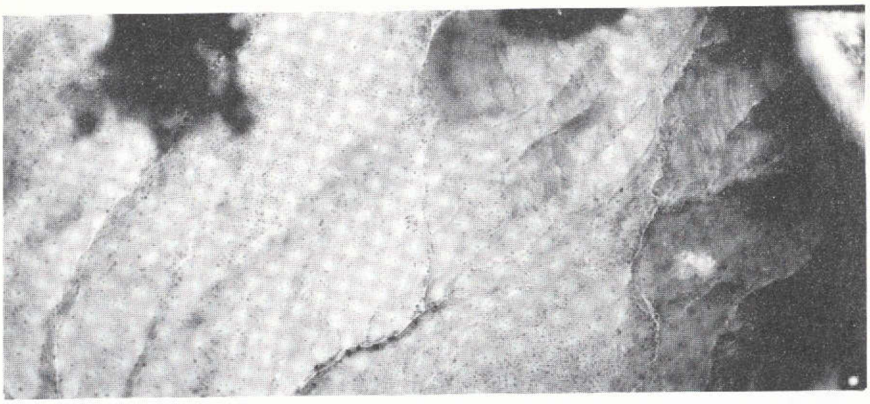


Figure 147c

Spectral Band — Red
Peak Wavelength — 700 nm
Peak Transmission — 90%
½ Bandpass — 110 nm
f/Number — 11

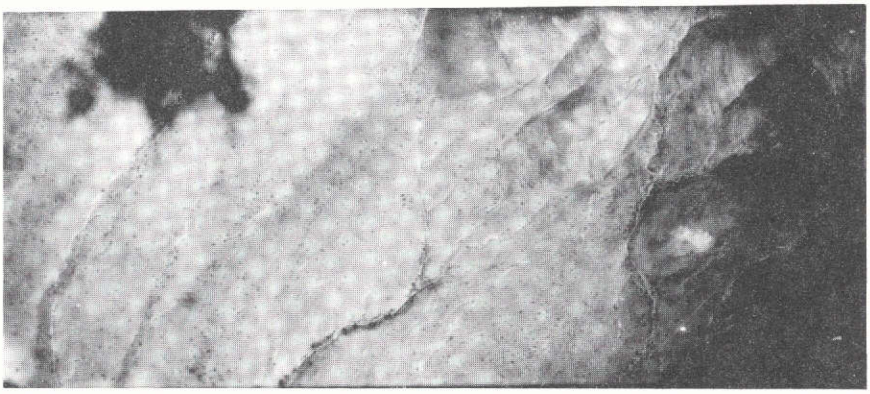


Figure 147d

Spectral Band — Near infrared
Peak Wavelength — 850 nm
Peak Transmission — 90%
½ Bandpass — 190 nm
f/Number — 16

Viewing Filters

Record	1	2	3	4
Filter	—	Blue	Green	Red
Saturation Level	—	90%	100%	85%

Evaluation of Multispectral Color Composite

— In an effort to differentiate between alluvium, limestone, dolomite, and limestone shale, Plate VIIa was generated using a recombination of Records #2, #3, and #4 projected as blue, green, and red respectively. This is an approximation to Eastman Kodak's color infrared film. In Plate VIIa some color difference does exist between the left portion of the photograph and the center; however, the extreme right-hand section containing the peak is heavily shadowed and so low in brightness that it is impossible to interpret what the composition of the soil might be. The isoluminous technique discussed in Section 12.1 was applied to this frame of data. The elimination of all brightness differences results in Plate VIIb. Alluvium is a pale blue, while the limestone dolomite area in the center of the photograph is a pinkish hue with the shale and limestone on the right-hand portion of the photograph being a deep cyan. One must remember that only differences in the spectral reflectance of the terrain are being imaged as colors in this rendition.

Test Site Description

WHITE MOUNTAIN, east of Bishop, California. This area of rough terrain contains a variety of deposits as well as a number of well-defined fault contacts. The mountains are sparsely covered with shrubbery and trees; due to the summer heat, many of the larger streams had already dried up by the beginning of August.

Targets to be Detected

- Sedimentary deposits
- Volcanics
- Fault contacts
- Sand and Granite

Flight Information

Date:	5 August 1967
Time:	1320 PDT
Altitude:	28,000 feet
Weather:	Clear
Film:	EK #5420
Filters:	Blue, green, red, infrared

Processing – Negative

Record	1	2	3	4
Gamma	1.2	1.9	1.8	2.0
Minimum Density	.16	.17	.11	.15

Processing – Positive

Record	1	2	3	4
Gama	1.5	2.0	1.8	1.6
Minimum Density	.17	.10	.11	.10

Ground Truth – See Figure 148d

Vol – Volcanic formations
Sed – Sedimentary rocks
G, S – Gravel, sand
Fault – Fault contacts

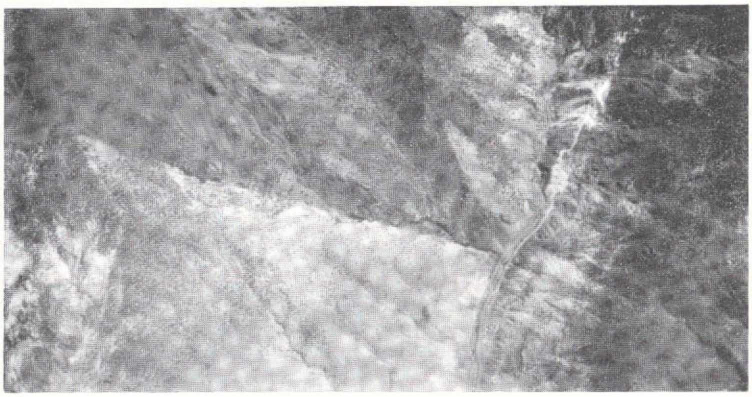


Figure 148a

Spectral Band — Blue
Peak Wavelength — 440 nm
Peak Transmission — 50%
½ Bandpass — 73 nm
f/Number — 8+ .1 ND

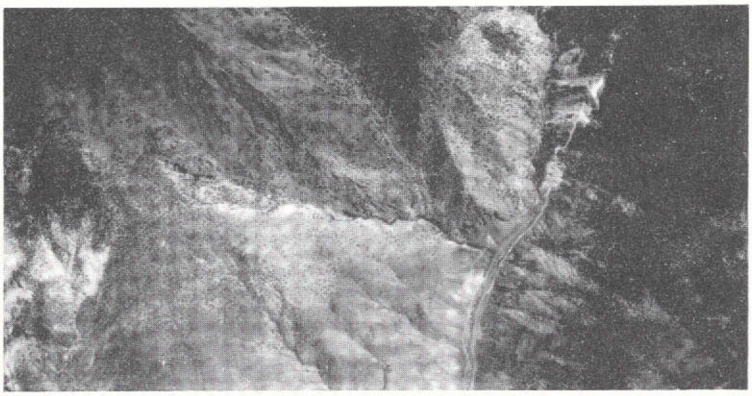


Figure 148b

Spectral Band — Green
Peak Wavelength — 530 nm
Peak Transmission — 54%
½ Bandpass — 67 nm
f/Number

Analysis of Black-and-White Positives

— The first record shown here is a broad band blue which traditionally lacks the contrast of the other records. It is, however, printed light for the purposes of color balancing and to increase the overall brightness of the composite multispectral image on the rear projection screen. Some brightness difference does exist, however, between the upper and lower portions of the image - volcanics and sediments respectively. The green spectral band contains both low minimum density and excellent contrast characteristics. Brightness differences between volcanics and sediments also exist in this record. Detail on the right portion of the photograph is lost due primarily to the presence of shadows. The red record shows very vividly the difference between volcanics and sediments. The shadow patterns in the upper portion of the photograph (volcanics) are not nearly as distinct in this record as in the green. This tends to enhance the overall difference between the two types of deposits. Notice that the blue, green, and red records have been processed such that the roadway running along the gravel and sand area has approximately the same density in each of the records. The infrared band was overexposed in the positive. This overexposure created greater densities which did not tend to mask any small differences which existed in the blue, green, and red spectral regions. Small differences in isolated areas of the volcanic section are lost in this infrared record and appear to be approximately as dense as the extreme right-hand portion of the photograph. Near-infrared reflectance for the sediments, as well as gravel and sand, is quite uniform.

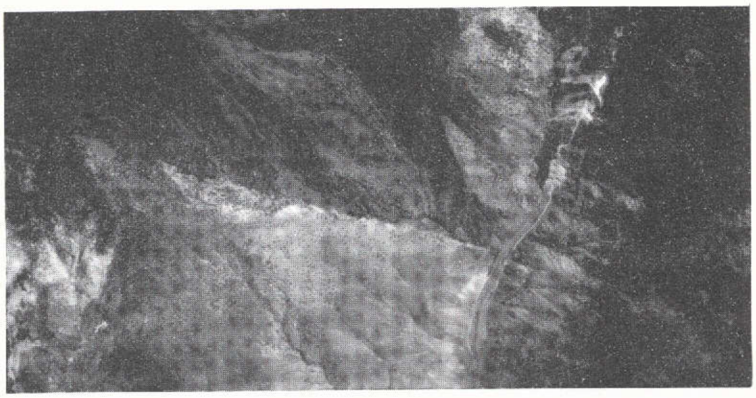


Figure 148c

Spectral Band — Red
Peak Wavelength — 700 nm
Peak Transmission — 50%
½ Bandpass — 110 nm
f/Number — 5.6 + .2 ND

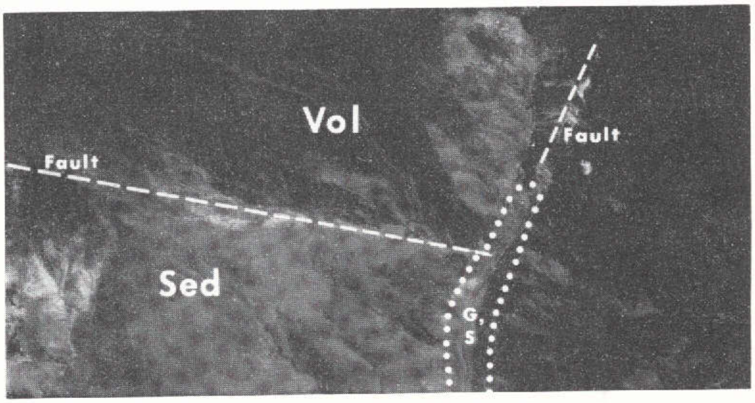


Figure 148d

Spectral Band — Near infrared
Peak Wavelength — 850 nm
Peak Transmission — 90%
½ Bandpass — 190 nm
f/Number — 11 + .8 ND

Viewing Filters

Record	1	2	3	4
Filter	Blue	Green	Red	—
Saturation Level	100%	—	100%	100%

Evaluation of Multispectral Color Composite

— The multispectral rendition of Plate VIIc has been produced by the recombination of Records #1, #3, and #4 projected as blue, green, and red respectively. Volcanics are shown as a deep orange, sedimentary deposits are a pinkish-gray, and the sand and gravel are a distinct white. The extreme right-hand portion of the photograph did contain some volcanic rock which is a deep blue-purple. The presence of the fault contacts is reasonably obvious in this multispectral rendition. Plate VIId is a conventional color infrared photograph exposed simultaneously with the multispectral imagery and processed by Data Corporation in Ohio. Little or no differentiation can be seen between the volcanics and the sediments. The fault contacts, if detectable at all, are only obvious because of the texture of the terrain.

Test Site Description:

OWENS DESERT, north of Bishop, California, is identified as Bishop Tuff. This relatively flat area has been extensively analyzed and maps have been generated showing the predominant geologic features. The flood plain deposits contain large amounts of vegetation and standing water bodies.

Targets to be Detected:

- Alluvium
- Non-Welded Tuff
- Partially-Welded Tuff
- Flood Plain Deposits

Flight Information

Date:	5 August 1967
Time:	1235 PDT
Altitude:	28,000 feet
Weather:	Clear
Film:	EK #5424
Filters:	Blue, green, red, infrared

Processing – Negative

Record	1	2	3	4
Gamma	1.8	2.1	2.0	2.1
Minimum Density	.6	.17	.11	.15

Processing – Positive

Record	1	2	3	4
Gamma	1.8	2.1	2.0	2.1
Minimum Density	.11	.11	.13	.12

Ground Truth – See Figure 149a

1 – Alluvium
2 – Non-welded tuff
3 – Partially-welded tuff
4 – Flood plain deposits

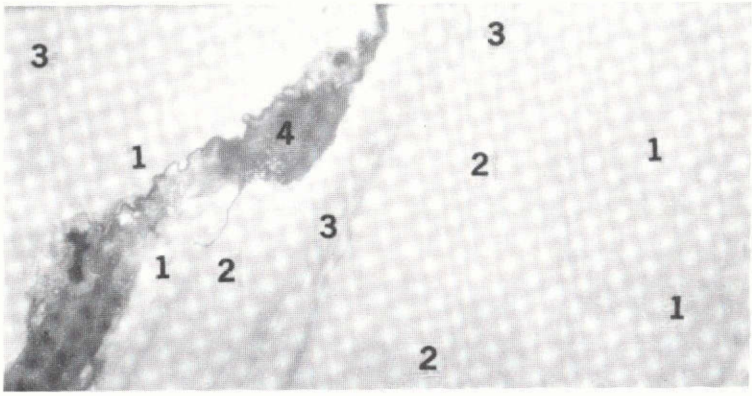


Figure 149a

Spectral Band — Blue
Peak Wavelength — 440 nm
Peak Transmission — 50%
½ Bandpass — 73 nm
f/Number — 8 + .1 ND

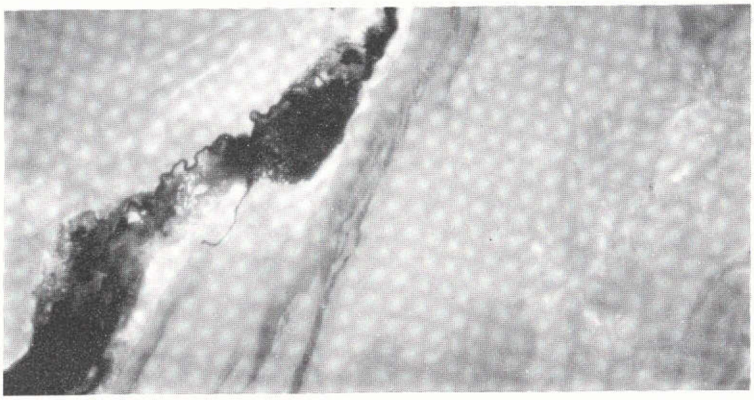


Figure 149b

Spectral Band — Green
Peak Wavelength — 530 nm
Peak Transmission — 54%
½ Bandpass — 67 nm
f/Number — 4

Analysis of Black-and-White Positives

— The blue band shows the usual lack of contrast in the overall scene. Only the area labelled 4 (flood plain deposits) is apparently different from the surrounding alluvium, non-welded tuff, and partially-welded tuff. The lack of detail in the blue record makes it suitable for either correcting the color balance of the final multispectral rendition or for increasing the overall brightness of the composite image. A set of color panels can be seen in the extreme upper portion of the photograph above the flood plain deposits. The green spectral record shows alluvium to be differentiated from both the flood plain deposits and the tuff areas. Excellent contrast and image detail are apparent in this record. The lower brightness associated with the alluvium and the partially-welded tuff to the right of the flood plain deposits is due primarily to the presence of small shadows. The red spectral band lacks the detail and contrast in the non-welded tuff which was apparent in the green record. Although an increase in the red contrast would have enhanced the areas marked 1, 2, and 3, it was purposely not increased to maintain the detail in the flood plain deposit area. Record #4, encompassing the near-infrared region, shows a marked difference in the flood plain deposits. The lush vegetation shows large infrared reflectance, while the surrounding geological areas are only as bright as that shown on the green spectral record. The processing of the four Bishop Tuff multispectral images was such that reproduction of the gray scale adjacent to the color panels was the same on each of the four images.

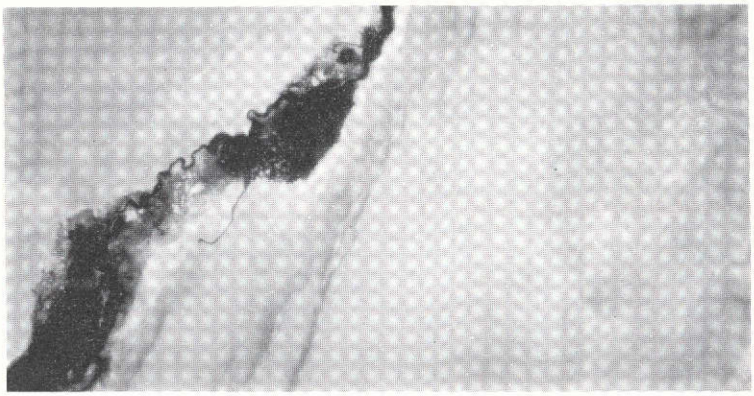


Figure 149c

Spectral Band — Red
Peak Wavelength — 700 nm
Peak Transmission — 50%
½ Bandpass — 110 nm
f/Number — 5.6 + .2 ND

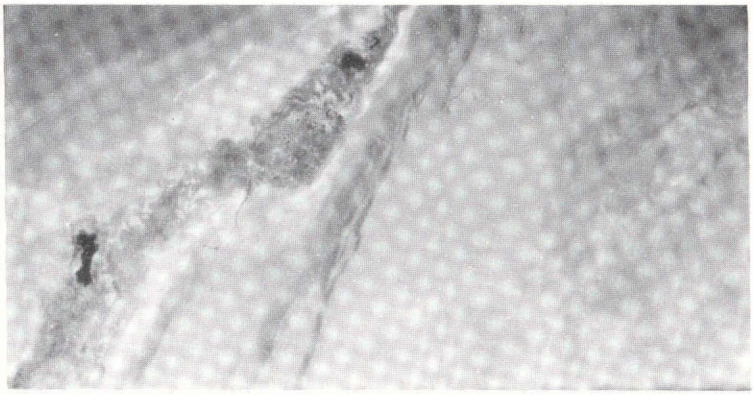


Figure 149d

Spectral Band — Near infrared
Peak Wavelength — 850 nm
Peak Transmission — 90%
½ Bandpass — 190 nm
f/Number — 11 + .8 ND

Viewing Filters

Record	1	2	3	4
Filter	—	Green	Blue	Red
Saturation Level	—	95%	70%	85%

Evaluation of Multispectral Color Composite

— The multispectral record shown in Plate VIIe is produced by an additive combination of Records #2, #3, and #4 projected as green, blue, and red respectively. This is a simulation of Eastman Kodak's Ektachrome infrared film, while Plate VIIf is a conventional color infrared photograph taken at exactly the same time as the multispectral. In Plate VIIe, the flood plain deposits have considerably more detail in them than the conventional infrared image as does the partially-welded tuff to the right of the flood plain deposit. The lack of color contrast in Plate VIIf is principally due to the fixed exposure ratio between the dye layers of the tri-pack emulsion. Alluvium tends to a whitish hue in both Plates VIIe and VIIf, while the non-welded tuff in Plate VIIe is a distinct yellow-green compared to a gray-green for the partially welded tuff. No such differentiation is possible in the conventional color infrared photograph of Plate VIIf.

APPLICATION — AGRICULTURE

Test Site Description

IMPERIAL VALLEY, CALIFORNIA, is located between the Salton Sea and the country of Mexico. It is a relatively flat terrain consisting of large tracts of cultivated land. It is surrounded by mountainous regions to the east and west.

Targets to be Detected

- Vegetation
- Water
- Soil

Flight Information

Date:	12 March 1969
Time:	0828 PST
Altitude:	129 miles
Weather:	Clear
Film:	EK #3400 and EK SO-246
Filters:	Green, red, infrared

Processing — Negative

Record	1	2	3	4
Gamma	3.2	2.9	1.6	—
Minimum Density	.62	.20	.12	—

Processing — Positive

Record	1	2	3	4
Gamma	3.16	2.64	2.64	—
Minimum Density	.12	.12	.14	—

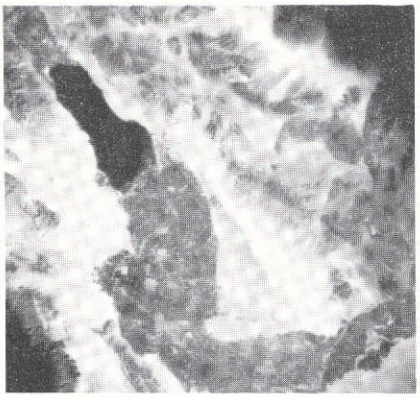


Figure 150a

Spectral Band — Green
Peak Wavelength — 530 nm
Peak Transmission — 54%
½ Bandpass — 67 nm
f/Number — 4

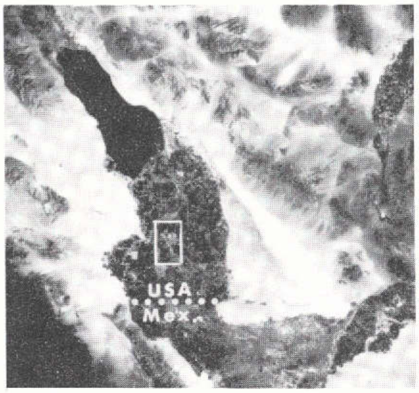


Figure 150b

Spectral Band — Red
Peak Wavelength — 700 nm
Peak Transmission — 50%
½ Bandpass — 110 nm
f/Number — 4

Analysis of Black-and-White Positives

— The first multispectral record of this Apollo 9 frame (blue) was reprocessed in order to decrease the maximum density of the image, as well as pull up the contrast. Some resolution has been lost due to the necessity of generating an intermediate negative; this positive is a third generation image. The contrast of this blue record is lower than that of the red and infrared records due to the large column of air between the ground and the spacecraft. Increasing the gamma to that of the red or infrared records resulted in a complete washout of the agricultural area south of the Salton Sea. Record #2, obtained through a broad band red filter, has excellent contrast and adequate positive printing exposure to maintain the density differences between the adjacent plots in the Imperial Valley area. The small blocked out region is that area of terrain which has been enlarged 20X in the following Figure 151. Although some large areas did fall on the shoulder of the characteristic curve, most exist along the straight line portion. The third multispectral record was exposed through a broad band near-infrared filter, namely 89B. The contrast and exposure is excellent for crop speciation and the Mexican-American border can clearly be seen by the wide difference in terrain brightness caused by the relative vigor of the crops.

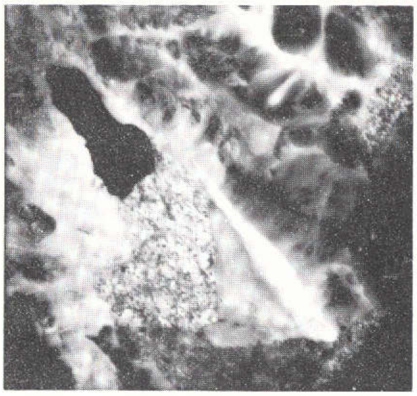


Figure 150c

Spectral Band — Near infrared
Peak Wavelength — 850 nm
Peak Transmission — 90%
½ Bandpass — 190 nm
f/Number — 16

The fourth camera of the Apollo 9 multispectral array contained a color infrared emulsion

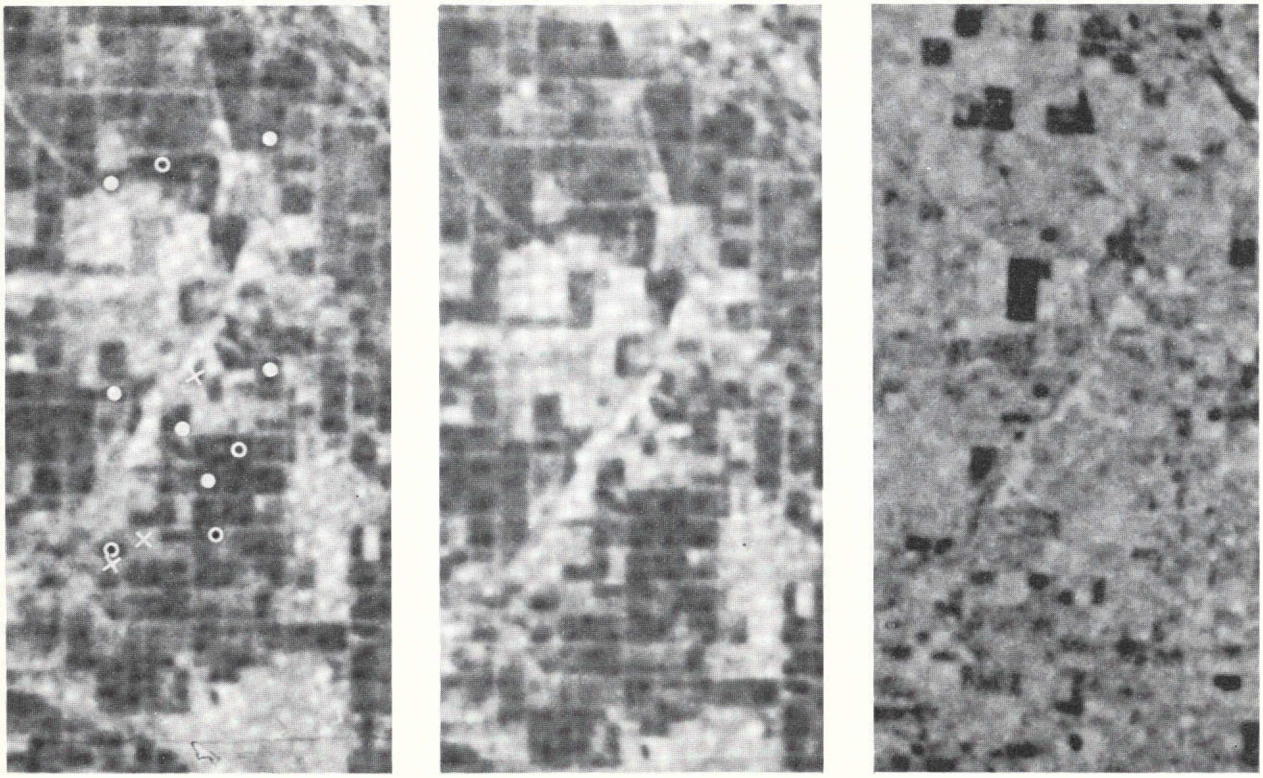
The multispectral rendition shown in Plate VIIIb was produced by projecting the green band as red, the red band as blue and the near infrared band as green. In this enlargement, barley, alfalfa, and sugar beets can be differentiated, although the visual color difference between them is not particularly obvious. The chormaticity diagram (shown in figure 152) shows the color separation between the crops which was measured from the multispectral viewing screen. Color differentiation between crops is possible from high altitudes using multispectral techniques.

Viewing Filters

Record	1	2	3	4
Filter	Red	Blue	Green	—
Saturation Level	80%	85%	90%	—

Evaluation of Multispectral Color Composite

— Plate VIIIa shows an additive recombination of the Apollo 9 multispectral imagery which was reprocessed by Long Island University. Records #1, #2, and#3 were recombined in additive synthesis using red, green, and blue filters respectively. The classification of vegetation, soil, and water in Plate VIIIa is reasonably apparent. Those areas which are green are vegetation, those areas which are brown are bare soil, and those presented as black are water.



Figures 151a, 151b and 151c are 20X enlargements of the green, red and near infrared bands for the small area of Imperial Valley shown in figure 150b. The ground truth, shown in figure 151a, is as follows:

X — Alfalfa
● — Safflower
o — Barley

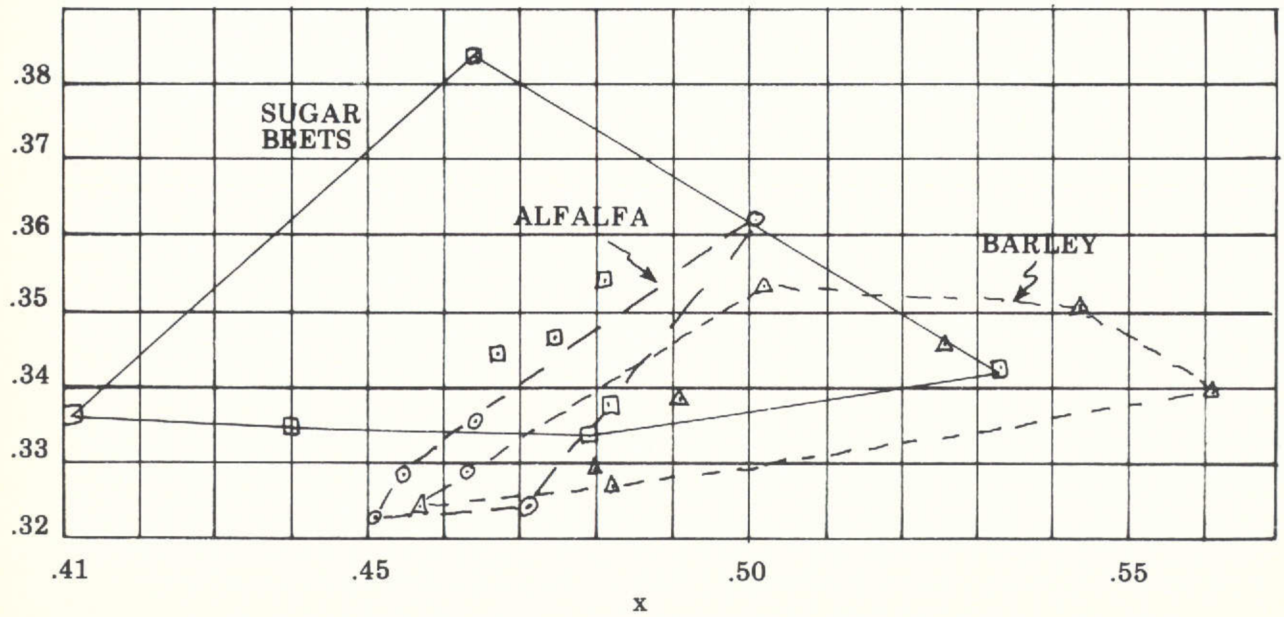


Figure 152: Chromaticity measurements of images of alfalfa, barley and sugar beets from the above color rendition.

Test Site Description

NELSPRUIT, SOUTH AFRICA is located in the Low Veld of the northern Transveld. The region is flat and dry requiring a large irrigation network to provide water to its citrus groves. This area is one of the experimental agricultural test stations for South Africa.

Targets to be Detected

- Root rot in avocado trees

Flight Information

Date:	October 1970
Time:	1420
Altitude:	2,000 feet
Weather:	Clear
Film:	EK #2424
Filters:	Infrared, red, none, infrared

Processing — Negative

Record	1	2	3	4
Gamma	1.8	2.0	2.1	2.1
Minimum Density	.10	.09	.11	.10

Processing — Positive

Record	1	2	3	4
Gamma	4.2	3.8	2.2	4.1
Minimum Density	.10	.12	.08	.09

Ground Truth — See figure 153b

Small groups of avocado trees infested with root rot disease have been marked.

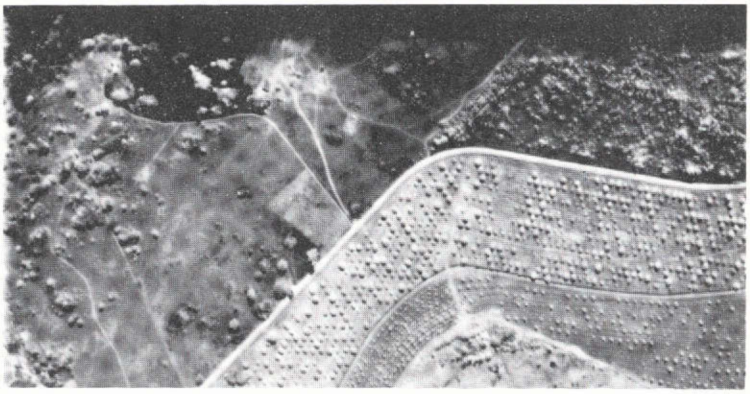


Figure 153a

Spectral Band — Near infrared
Peak Wavelength — 850 nm
Peak Transmission — 70%
½ Bandpass — 38 nm
f/Number — 8

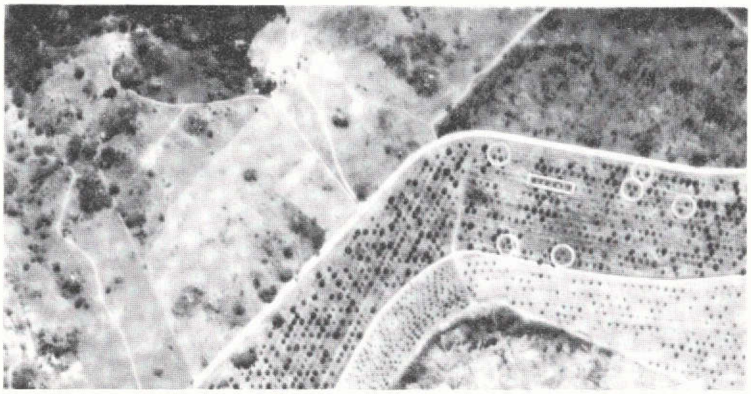


Figure 153b

Spectral Band — Red
Peak Wavelength — 625 nm
Peak Transmission — 50%
½ Bandpass — 43 nm
f/Number — 5.6

Analysis of Black-and- White Positives

— These four multispectral images have been exposed, printed, and processed very well for the overall scene. The infestation of avocado root rot disease is not visually detectable. As a result the circled clusters of trees in the grove do not appear to be any less or more dense than the healthy trees surrounding them. An examination of the color plates associated with this black-and-white frame will indicate that pre-visual detection of this infestation is not possible using conventional multispectral viewing techniques. Special processes, however, have been developed in order to provide the observer with a pre-visual detection of the infestation. Examination of these black-and-white images shows that those trees which have been diseased are generally not as vigorous and do not have the crown size of those which are healthy.

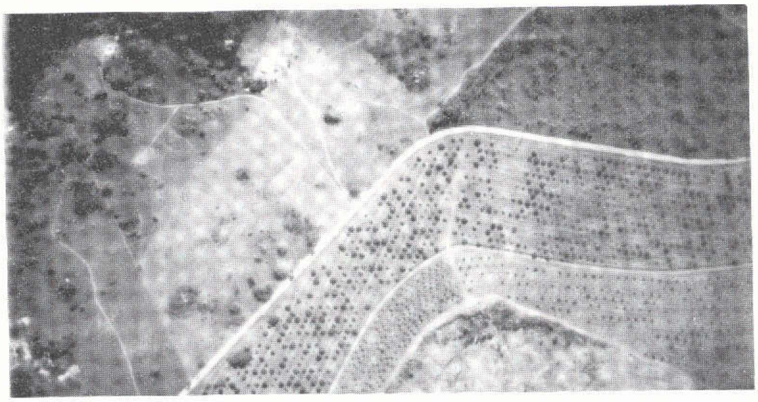


Figure 153c

Spectral Band —
Peak Wavelength —
Peak Transmission —
½ Bandpass —
f/Number — 16

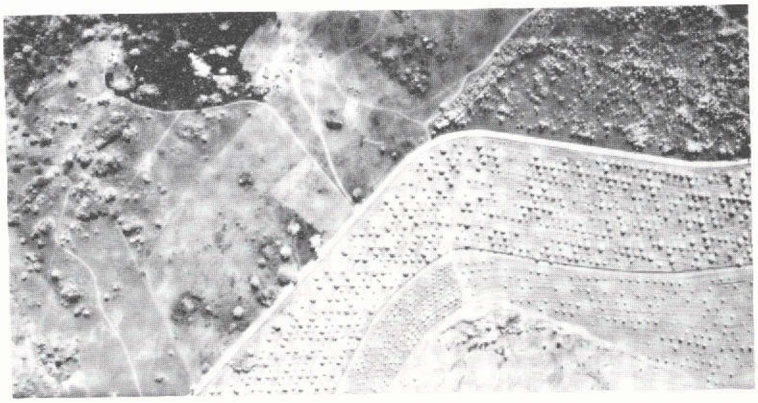


Figure 153d

Spectral Band — Near infrared
Peak Wavelength — 725 nm
Peak Transmission — 80%
½ Bandpass — 31 nm
f/Number — 8

Viewing Filters

Record	1	2	3	4
Filter	Green	Green	—	Red
Saturation Level	100%	30%	—	70%

Evaluation of Multispectral Color Composite

— The multispectral rendition shown in Plate VIIIc was reproduced using a combination of Records #1, #2, and #4 projected as green, green, and red respectively. Bands 1 and 2 were both projected as green in an effort to enhance the diseased trees. Unfortunately, however, the pre-visual detection using conventional multispectral techniques was not possible in this particular rendition. However, Plate VIIId was reproduced using an isoluminous procedure and the diseased trees are fairly obvious as red, while those that are healthy are yellow. Previsual detection is possible using a differential masking technique, in spite of the fact that it is not at all obvious on conventional multispectral imagery. The reader should note that exactly the same negatives were used to produce Plates VIIIc and VIIId; the additional enhancement associated with Plate VIIId is a result of processing only.

APPLICATION — AGRICULTURE

Test Site Description

DAVIS, is an Agricultural Experimental Test Station associated with the University of California, just west of Sacramento. The area is characterized by the cultivation of a wide variety of agricultural crops, many of which are at different stages of vigor and maturity. The area has been extensively analyzed and excellent ground truth is available for most of it.

Targets to be Detected

- Alfalfa
- Corn
- Barley
- Tomatoes

Flight Information

Date:	20 July 1969
Time:	1425 PDT
Altitude:	15,000 feet
Weather:	Clear
Film:	EK #5424
Filters:	Blue, green, red, infrared

Processing — Negative

Record	1	2	3	4
Gamma	1.0	1.0	1.0	.98
Minimum Density	.02	.17	.09	.22

Processing — Positive

Record	1	2	3	4
Gamma	1.7	1.4	1.1	1.5
Minimum Density	.15	.2	.16	.18

Ground Truth — See figure 154b

S—	Safflower
C —	Corn
BS	Bare Soil
N —	Beans
A	Alfalfa
R —	Rye
B—	Barley
E —	Tomatoes

Figure 154a

Spectral Band — Blue
Peak Wavelength — 440 nm
Peak Transmission — 50%
½ Bandpass — 73 nm
f/Number — 16

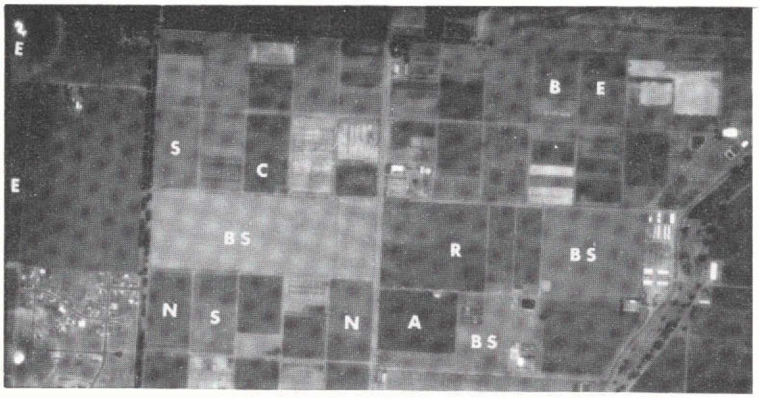


Figure 154b

Spectral Band — Green
Peak Wavelength — 530 nm
Peak Transmission — 54%
½ Bandpass — 67 nm
f/Number — 16

Analysis of Black-and-White Positives

— Record #1, taken through a broad band blue filter, shows the usual lack of contrast; this is due to the fact that the imagery was taken at an altitude of 15,000 feet at 2:30 in the afternoon and the presence of haze was obvious, although the day was clear. Increasing the printing exposure in order to enhance the darker areas of the photograph would have resulted in an increase in the minimum density or the addition of an overall gray to the photograph. Record #2, exposed through the green spectral region, has good contrast; this can be seen by examining the white and black areas on the right-hand portion of the photograph. This record was purposely printed on the heavy side in order to reduce the overall brightness of the crops in the green spectral region. Since what we are looking for in multispectral photography are density differences between objects of interest, it is not desirable that any one spectral band predominate in brightness over the other three. The third multispectral record, exposed through a broad band red filter, shows excellent contrast and large density differences between the crops in the area. It should be noted that each of these records was exposed and processed so that the gray panels on the ground appeared neutral when recombined in true color on the multispectral viewer. The typical high reflectance in the near-infrared spectral region for lush crops can be seen in the black-and-white positive print of the fourth spectral record. An example of good filter selection is apparent upon examination of Records #4 and #3. If one looks at the bare soil area in the lower center portion of the photograph on the near-infrared record, it is a darkish gray. In Record #3 the same bare soil plot has a very low density. Compare these to the alfalfa which lies diagonally to

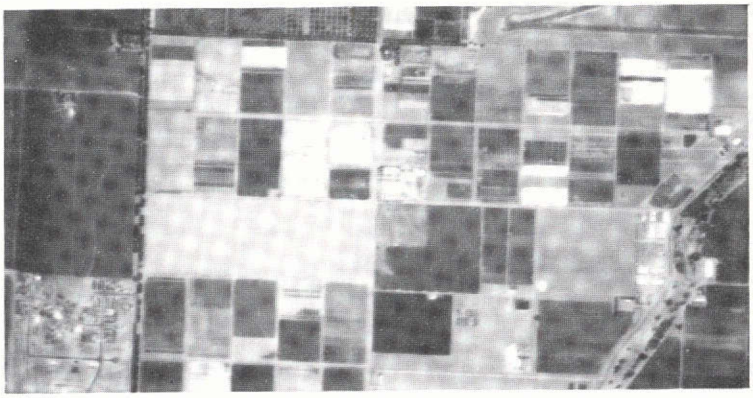


Figure 154c

Spectral Band — Red
Peak Wavelength — 700 nm
Peak Transmission — 50%
½ Bandpass — 110 nm
f/Number — 16

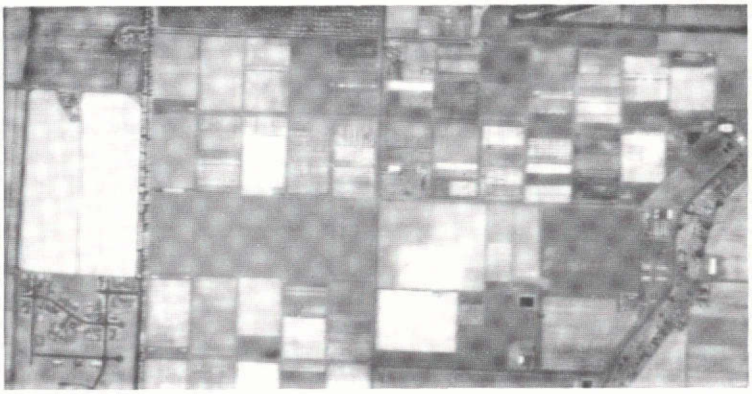


Figure 154d

Spectral Band — Near infrared
Peak Wavelength — 850 nm
Peak Transmission — 90%
½ Bandpass — 190 nm
f/Number — 16

the right of this bare soil field; in the near-infrared record this alfalfa stand is a very low density, whereas on the red record it is black. This density reversal from one band to the next additively produces two areas which are widely separated in color.

Viewing Filters

Record	1	2	3	4
Filter	—	Blue	Green	Red
Saturation Level	—	100%	50%	18%

Evaluation of Multispectral Color Composite

— The multispectral rendition shown in Plate VIIIe is a simulation of color infrared film reproduced by the combination of Records #2, #3, and #4 projected as blue, green, and red respectively. A good many of the crops contained in this photograph can be differentiated on the basis of their color without any auxiliary equipment. It was necessary, however, in differentiating corn, alfalfa, and tomatoes to use a colorimeter in order to chromatically separate the individual crops. These measurements are shown in the chromaticity diagram (figure 155) and extensive measurements throughout the roll film showed that all alfalfa, barley, corn and tomatoes fell within the convex sets shown in the diagram.

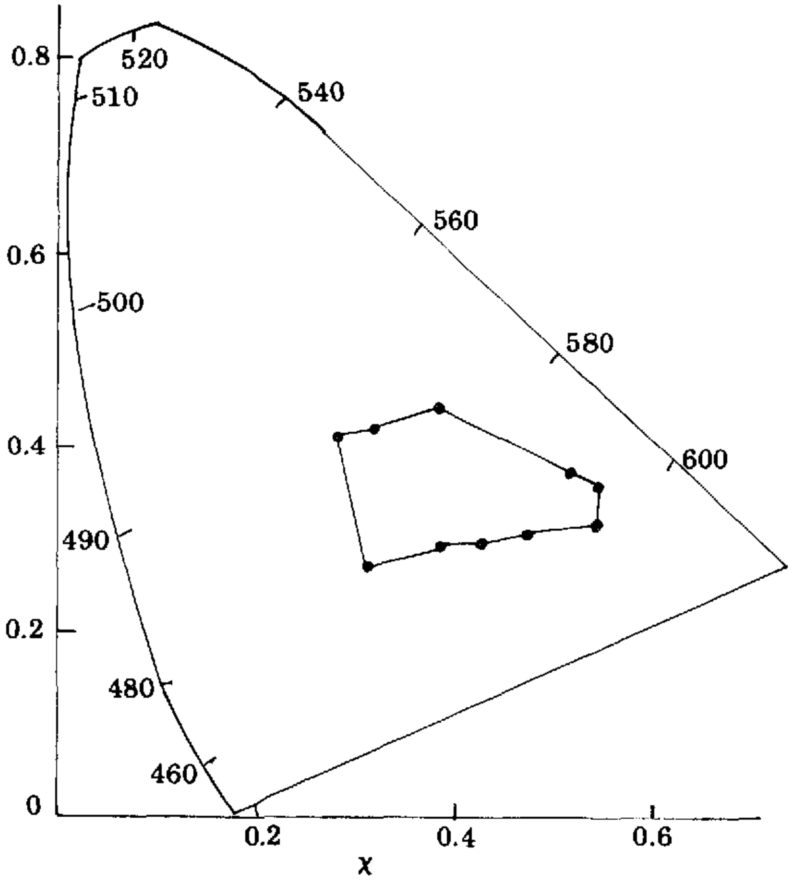


Figure 155. Chromaticity diagram showing convex polygon for different crop measurements in color rendition shown in Plate VIIIe.

APPLICATION — AGRICULTURE

Test Site Description

IMPERIAL VALLEY, CALIFORNIA lies in the extreme south-central part of California. The valley extends from the Salton Sea on the north to the Mexican border on the south and has an areal extent of about 4500 square miles. With almost a half million acres of cropped land, the Imperial Valley is the largest single area of irrigated agriculture in the Western Hemisphere.

Targets to be Detected

- Alfalfa or rye grass
- Cotton
- Sorgum
- Bare soil

Flight Information

Date:	29 July 1969
Time:	1520 PDT
Altitude:	17,500 feet
Weather:	Clear
Film:	EK #5424
Filters:	Infrared, red, green, blue

Processing — Negative

Record	1	2	3	4
Gamma	1.5	1.85	.98	1.67
Minimum Density	.12	.19	.10	.20

Processing — Positive

Record	1	2	3	4
Gamma	3.1	3.0	3.2	2.2
Minimum Density	.27	.29	.31	.34

Ground Truth — See figure 156b

A,R — alfalfa or rye grass
B — bare soil
C — cotton
S — sorgum

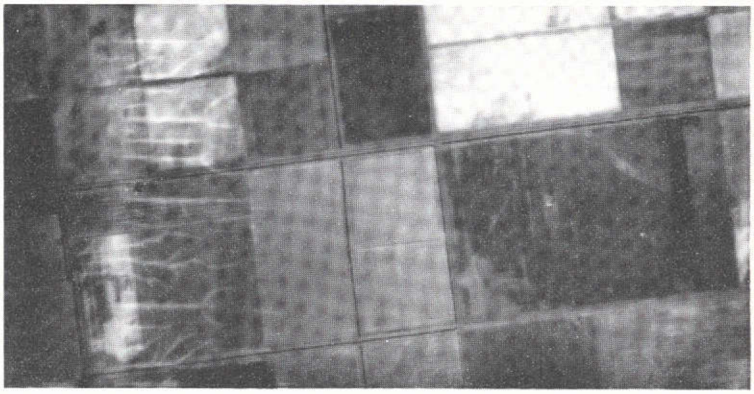


Figure 156a

Spectral Band — Infrared
Peak Wavelength — 850 nm
Peak Transmission 90%
½ Bandpass — 190 nm
f/Number — 16

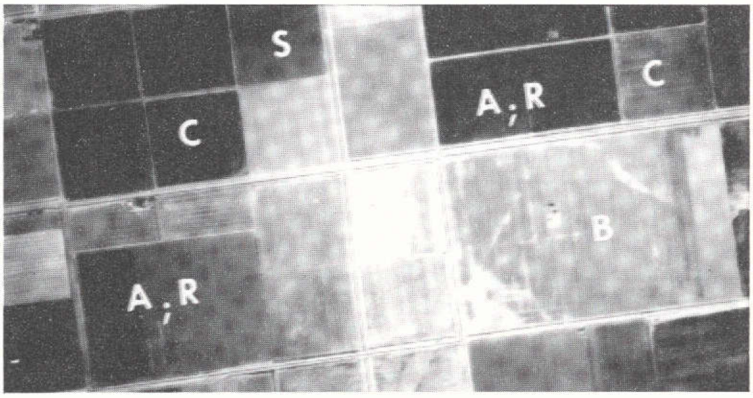


Figure 156b

Spectral Band — Red
Peak Wavelength — 700 nm
Peak Transmission — 50%
½ Bandpass — 110 nm
f/Number — 4 + .2 ND

Analysis of Black-and-White Positives

— Each of the four multispectral records for this frame of data have been somewhat overexposed in order to preserve the detail in the areas labelled alfalfa, or rye grass, and barley. The contrast was increased for each record to the point where the densest regions fell along the shoulder of the characteristic curve. The differences in spectral reflectance between the crops for the narrow band filters used were widely different so that it was difficult, at best, to place all the crops in each of the records along the straight line portion. Only the blue spectral region possesses an overall set of densities which could be placed along the straight line. The horizontal lines in Records #2 and #4 are static marks caused by the use of an acetate base film.

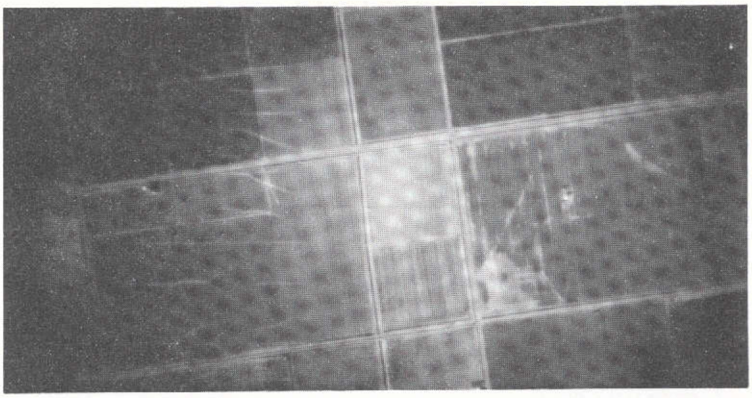


Figure 156c

Spectral Band — Green
Peak Wavelength — 530 nm
Peak Transmission — 54%
½ Bandpass — 67 nm
f/Number — 2.5

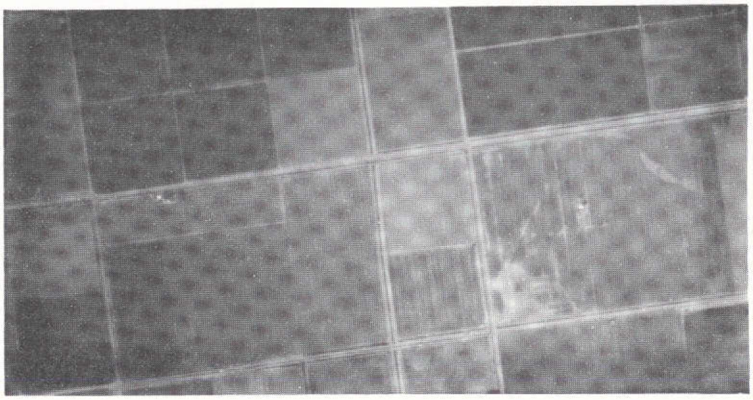


Figure 156d

Spectral Band — Blue
Peak Wavelength — 440 nm
Peak Transmission — 50%
½ Bandpass — 73 nm
f/Number — 8

Viewing Filters

Record	1	2	3	4
Filter	Red	Green	Blue	—
Saturation Level	95%	90%	70%	—

Evaluation of Multispectral Color Composite

— The multispectral rendition shown in Plate VIIIf was produced with the additive combination of Records #1, #2, and #3 projected as red, blue, and green respectively. Here, safflower tends to a reddish-orange, corn is a vivid red, while alfalfa or rye grass on the upper portion of the photo is a red-magenta. The alfalfa or rye grass shown in the lower left-hand portion of the photograph was sparse and spotty and accurate chromatic measurement of this area was not possible. Barley was additively presented as a pure gray.

APPLICATION — FORESTRY

Test Site Description

YOSEMITE VALLEY, CALIFORNIA. This area is located in the center of the Yosemite National Park. A variety of conifers and hardwoods make up the bulk of the vegetation. Lush meadow areas exist, generally adjacent to the rapid flowing streams.

Targets to be Detected

Yosemite

- Coniferous forest stands (pine, incense cedar)
- Hardwood trees (oak)

Flight Information

Date:	21 July 1969
Time:	1120 PDT
Altitude:	9,500 feet
Weather:	Clear
Film:	EK #2424
Filters:	Infrared, green, red, infrared

Processing — Negative

Record	1	2	3	4
Gamma	2.2	2.0	1.8	.48
Minimum Density	.32	.11	.10	.21

Processing — Positive

Record	1	2	3	4
Gamma	1.03	1.3	1.8	2.0
Minimum Density	.19	.07	.08	.09

Ground Truth — See figure 157d

P — Pine
O — Oak
I — Incense cedar

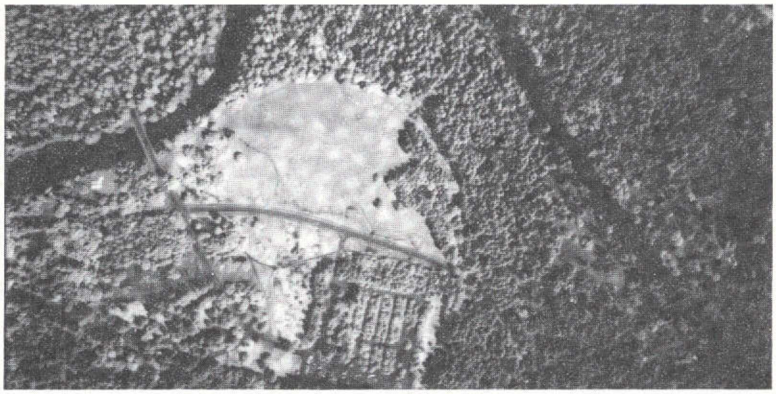


Figure 157a

Spectral Band — Near infrared
Peak Wavelength — 754 nm
Peak Transmission — 84%
½ Bandpass — 39 nm
f/Number — 5.6

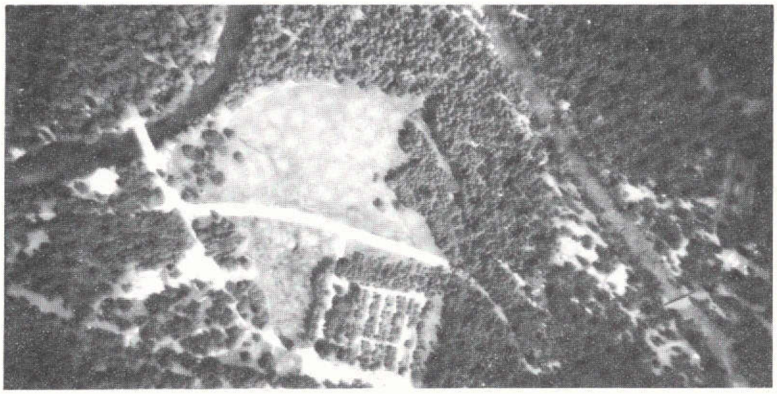


Figure 157b

Spectral Band — Green
Peak Wavelength — 553 nm
Peak Transmission — 52%
½ Bandpass — 46 nm
f/Number — 2.5 + .1 ND

Analysis of Black-and-White Positives

— The first multispectral record exposed in the near-infrared portion of the spectrum shows excellent differentiation between hardwood and conifers. Although the exposure was somewhat on the heavy side, the hardwood trees are quite obvious, especially in the right-hand portion of the photograph. Record #2, exposed through a green filter, has been printed and processed in order to maximize any small differentiation which may exist between the conifers and hardwoods at the upper center portion of the photograph. Nevertheless, there was little spectral difference between these tree types in the green region. The third multispectral record (red) has been exposed and processed for the overall scene because little or no differentiation was possible between hardwoods and conifers in this record. This band does, however, give a substantial amount of detail in the grass meadowland in the center of the photo. The fourth multispectral record (a second near-infrared band) has been exposed and processed for the center portion of the photograph. The discrimination between hardwoods and conifers is not as distinct as it was in the first multispectral record and much of the detail which was present in Record #3 in the grassy area in the center has been lost. It may be concluded from an examination of these four bands that the two infrareds are the best selection for differentiating between the two types of forest stands. When an image such as Record #1 is projected as green and Record #3 is projected as red, there results a chromatic differentiation produced by the density differences between the photos. Also, the detail which was not present in Record #1 of the grassy areas will become apparent when projecting Record #3. Differentiation between two types of conifers, namely pine and incense cedar, is not plainly obvious on any of these multispectral images.

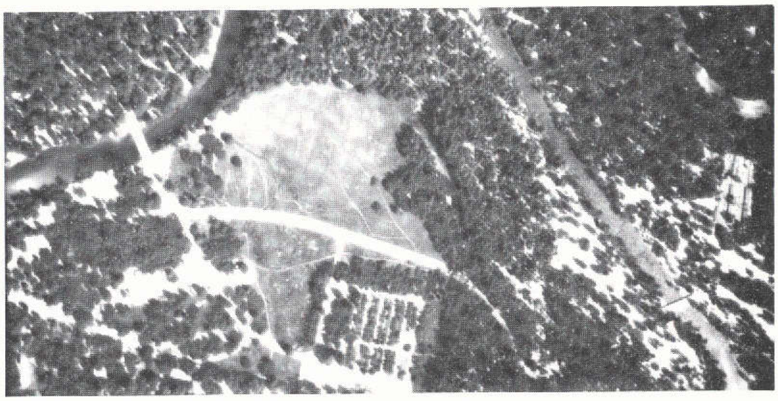


Figure 157c

Spectral Band — Red
Peak Wavelength — 682 nm
Peak Transmission — 80%
½ Bandpass — 31 nm
f/Number — 4

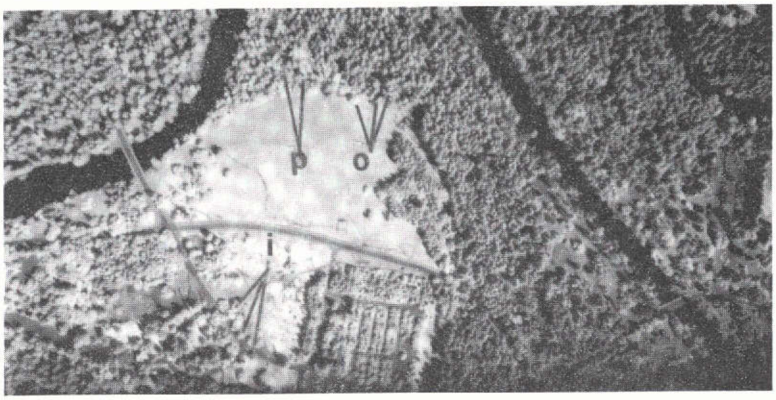


Figure 157d

Spectral Band — Near infrared
Peak Wavelength — 849 nm
Peak Transmission — 70%
½ Bandpass — 38 nm
f/Number — 4 + .2 ND

Viewing Filters

Record	1	2	3	4
Filter	Green	Red	Blue	—
Saturation Level	100%	100%	100%	—

Evaluation of Multispectral Color Composite

The false color multispectral rendition shown in color Plate IXa, was produced by projecting records 1, 2 & 3 as green, red and blue, respectively. The deciduous trees are a vivid pea green because:

- they reflect heavily in the near infrared (projected as green)
- they possess the characteristic green color (projected as red)

Since the infrared reflectance is greater than the green, the resultant additive color for these trees is brown, brownish purple and brownish red. It is not possible to differentiate between the incense cedar and the pine.

Test Site Description

MEADOW VALLEY, Bucks Lake. This region contains areas which are primarily covered with either high density conifers or meadow hardwoods. The Bucks Lake area is a forestry test site. The ground truth associated with it is very complete.

Targets to be Detected

- High-medium density conifers
- Low density conifers
- Meadow and Riparian hardwoods
- Rock, water

Flight Information

Date:	21 July 1969
Time:	1330 PDT
Altitude:	19,000 feet
Weather:	Clear
Film:	EK #5424
Filters:	Infrared, red, green, blue

Processing — Negative

Record	1	2	3	4
Gamma	2.2	2.0	1.8	.48
Minimum Density	.32	.11	.10	.21

Processing — Positive

Record	1	2	3	4
Gamma	1.03	1.3	1.8	2.0
Minimum Density	.19	.07	.08	.09

Ground Truth — See figure 158d

1 — Medium-high density conifers
2 — Low-density conifers
4 — Meadow and riparian hardwoods
5 — Bare soil and rock

Figure 158a

Spectral Band — Near infrared
Peak Wavelength — 850 nm
Peak Transmission — 90%
½ Bandpass — 190 nm
f/Number — 16

Figure 158b

Spectral Band — Red
Peak Wavelength — 700 nm
Peak Transmission — 50%
½ Bandpass — 110 nm
f/Number — 4 + .2

Analysis of Black-and-White Positives

— Multispectral Record #1 (near-infrared) has been well-exposed and processed for the two major types of vegetation in the area (conifers and hardwoods). The extreme spectral absorption of near-infrared radiation by water masses makes the stream in the upper portion of this photograph distinctly vivid. The three vertical lines at the bottom of this multispectral band were caused by static in the camera. This is primarily due to the use of an acetate-base film. Such static markings appear in dry climates at high altitudes using this particular film base. Near-infrared sensitive emulsions developed since 1969, however, use an estar base which is not prone to building up a static charge on it. The second multispectral record (red) has been processed to a gamma such that the detail in the vegetation has been placed on the straight line portion of the characteristic curve. The exposure is somewhat heavy in areas labelled 1 in order to maintain the detail in the areas labelled 4. The third spectral band (green) has also been processed to a reasonably high gamma to increase the color differentiation between the vegetation groups. Slight overexposure in the positive was necessary in order to maintain detail in areas labelled number 4. The general effect of increasing the exposure consists of lowering the resultant screen brightness on the multispectral viewer. Nevertheless it is the best compromise between scene brightness and image detail. The fourth multispectral record (blue) has been processed (as the infrared has) to a nominal gamma since both the conifers and the hardwoods reflect approximately the same; all vegetation appears on the straight line portion of the characteristic curve. The apparent lack of contrast is the result of areas 1 and 4 having a relatively small difference in density between them.

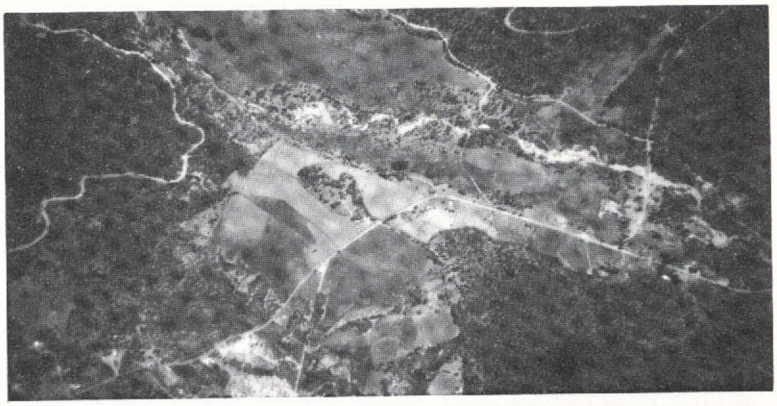


Figure 158c

Spectral Band — Green
Peak Wavelength — 530 nm
Peak Transmission — 54%
½ Bandpass — 67 nm
f/Number — 2.5

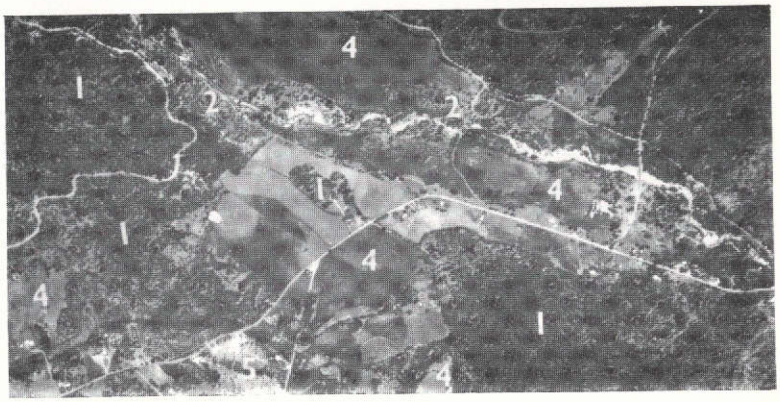


Figure 158d

Spectral Band — Blue
Peak Wavelength — 440 nm
Peak Transmission — 50%
½ Bandpass — 73 nm
f/Number — 8

Viewing Filters

Record	1	2	3	4
Filter	Green	Red	Blue	—
Saturation Level	66%	66%	66%	—

Evaluation of Multispectral Color Composite

— The additive rendition shown in Plate IXb is a result of recombining Records #1, #2, and #3 as green, red, and blue respectively. The low image density values on Record #1 for the areas marked 1 renders them a deep green in Plate IXb. Wide differences in color existed in areas marked 4, meadow and riparian hardwoods; they reproduced as a deep brown to a pink or a very light green. The low density conifers can easily be seen as the dark green against a pinkish background; the dark green results from the vegetation itself, while the pink background is the soil which surrounds them.

Test Site Description

BUCKS LAKE, California. This area is heavily forested with stands of dense conifers. Some riparian and meadow hardwoods exist between these areas as well as lush meadowlands.

Targets to be Detected

- High density conifers
- Meadow and riparian hardwoods
- Water

Flight Information

Date:	21 July 1969
Time:	1250 PDT
Altitude:	18,000 feet
Weather:	Clear
Film:	EK #2424
Filters:	Infrared, red, green, blue

Processing — Negative

Record	1	2	3	4
Gamma	2.2	2.0	1.8	.48
Minimum Density	.32	.11	.10	.21

Processing — Positive

Record	1	2	3	4
Gamma	—	—	—	—
Minimum Density	.19	.07	.08	.09

Ground Truth — See figure 159d

1 — Medium-high density conifers
2 — Low-density conifers
4 — Meadow and riparian hardwoods
6 — Water

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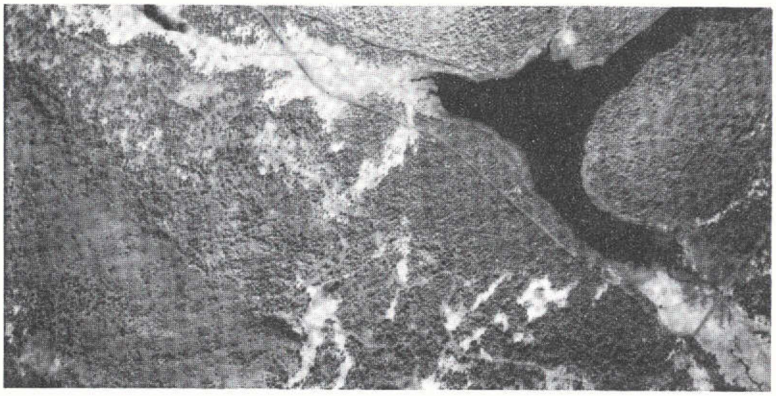

Figure 159a

Spectral Band — Near infrared
Peak Wavelength — 850 nm
Peak Transmission — 90%
½ Bandpass — 190 nm
f/Number — 16

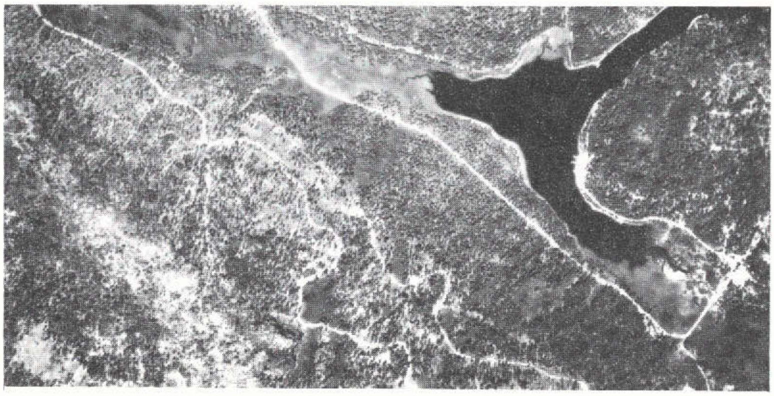

Figure 159b

Spectral Band — Red
Peak Wavelength — 700 nm
Peak Transmission — 50%
½ Bandpass — 110 nm
f/Number — 4 + .2 ND

Analysis of Black-and-White Positives

— The exposure and processing of the first record (near-infrared) is optimal for imaging of both conifers and hardwoods. Some increase in exposure would have picked up the detail in the areas labelled 4; however, this would only be accomplished at the sacrifice of detail in the areas labelled 1 and 2. In this particular record, the low-density conifers are somewhat difficult to see and an increase in the minimum density would have rendered them approximately the same as areas labelled 1. In Record #2 (red), we see a vivid difference between the medium-to-high density conifers and the low-density conifers. The exposure for this record is light, but this was purposely done in order to preserve the detail which existed in the negative for area #4 on the right-hand portion of the photograph. The third spectral band (green) has been exposed principally for the hardwood sites in the center portion of the photograph. Increasing the contrast in order to maximize the density difference between areas 1 and 4 resulted in the high density conifers at the edges of the photographs to fall on the low shoulder portion of the characteristic curve. Record #4, exposed through a broad band blue filter, shows that little or no spectral difference exists between the hardwoods in site 4 and the high-density conifers labelled 1. It was interesting to note that on the blue record some water detail was visible in the negative, although processing conditions for this set of multispectral records did not permit enhancement of this area.

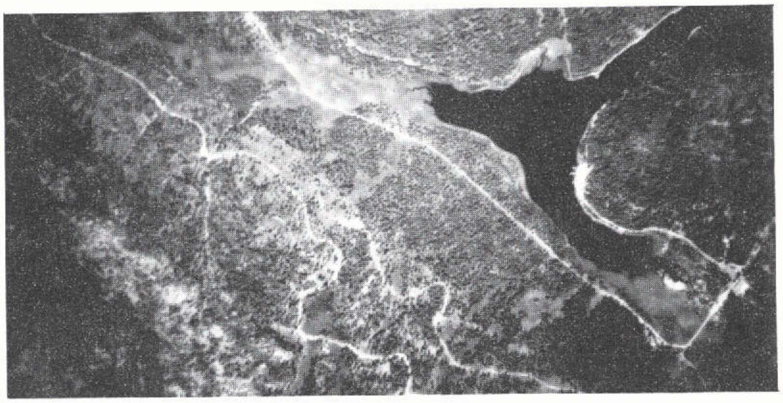

Figure 159c

Spectral Band — Green
Peak Wavelength — 530 nm
Peak Transmission — 54%
½ Bandpass — 67 nm
f/Number — 2.5

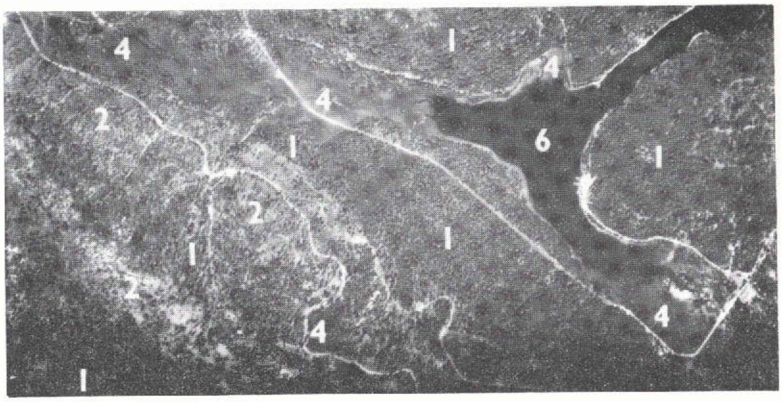

Figure 159d

Spectral Band — Blue
Peak Wavelength — 440 nm
Peak Transmisson — 50%
½ Bandpass — 73 nm
f/Number — 8

Viewing Filters

Record	1	2	3	4
Filter	Blue	Red	Green	—
Saturation Level	50%	70%	70%	—

Evaluation of Multispectral Color Composite

— The multispectral rendition, as shown in Plate IXc, has been produced by a recombination of Records #1, #2, and #3 projected as blue, red, and green respectively. All sites labelled as 1 are predominately a bluish color owing to the low image density of the #1 record. The low-density conifers of area 2 can be seen as a spotted blue color against a bluish-yellow background which represents the soil. The meadow and riparian hardwoods lie between a light blue and a blue-yellow hue because of the background soil. All watered areas are black owing to the high absorption of the radiation in each spectral region. The deep blue associated with the high-density conifers on the extreme right-hand portion of the photograph is some indication of the closeness of the stands. The compactness of the trees in any given areas can be measured colorimetrically by using a large aperture (4mm) on a colorimeter sensing head. In regions where the conifers are tightly packed together, the color will be a pure hue as shown in Plate IXc, right side. In regions where the conifers are less dense, the color will be some combinaton of the soil and vegetation hues as shown in the center of Plate IXc.

Test Site Description

BUCKS LAKE, California. This region of the Bucks Lake forestry test site contains a wide variety of conifers and hardwoods. A large amount of bare soil and rock is present adjacent to the small bodies of water.

Targets to be Detected

- High density conifers
- Brush and meadow hardwoods
- Soil and rock
- Water

Flight Information

Date:	21 July 1969
Time:	1320 PDT
Altitude:	19,000 feet
Weather:	Clear
Film:	EK #2424
Filters:	Infrared, red, green, blue

Processing – Negative

Record	1	2	3	4
Gamma	2.2	2.0	1.8	.48
Minimum Density	.32	.11	.10	.21

Processing – Positive

Record	1	2	3	4
Gamma	1.03	1.3	1.8	2.0
Minimum Density	.19	.07	.08	.09

Ground Truth – see figure 160d

1 - Medium-high density conifers
3 - Brush and dry site hardwoods
4 - Meadow and riparian hardwoods
5 - Bare soil and rock
6 - Water

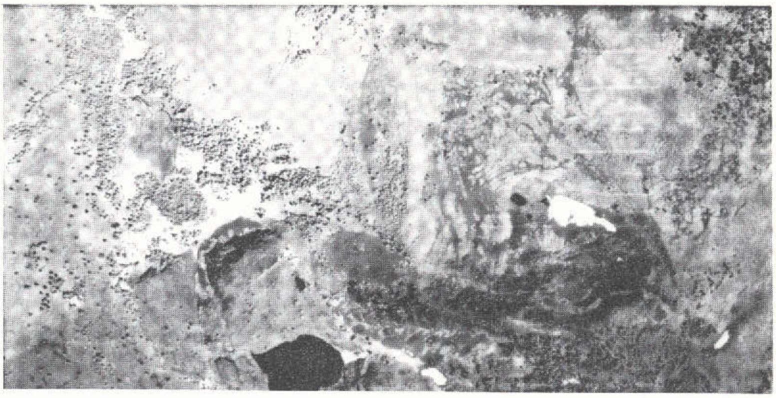

Figure 160a

Spectral Band — Near infrared
Peak Wavelength — 850 nm
Peak Transmission — 90%
½ Bandpass — 190 nm
f/Number — 16

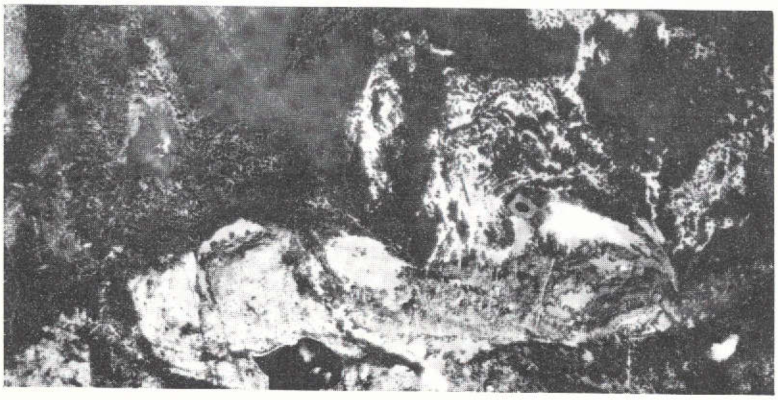

Figure 160b

Spectral Band — Red
Peak Wavelength — 700 nm
Peak Transmission — 50%
½ Bandpass — 110 nm
f/Number — 4 + .2 ND

Analysis of Black-and-White Positives

— The positive printing exposure and processing of each of these four multispectral records is excellent for the targets under consideration. The tonal values of spectral band #1 (near-infrared) are distinctly different from the other three, especially in the areas labelled as 3, 4, and 5. The short horizontal lines which can be seen on the right portion of Records #1 and #3 are static marks in the negative itself. These static marks are generally visible when one flies at high altitudes in dry climates using a film emulsion having an acetate base.

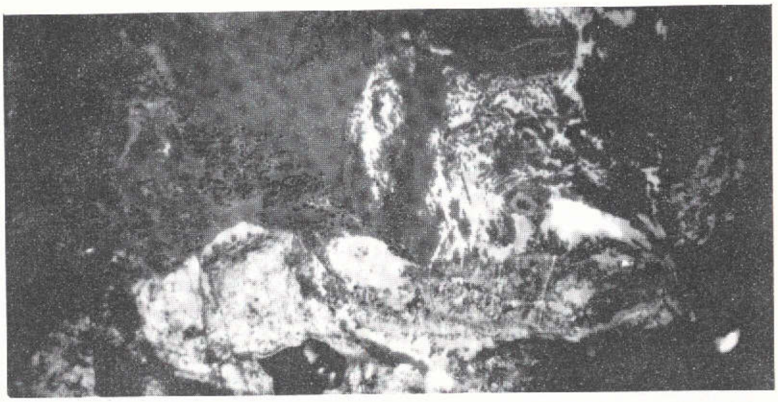

Figure 160c

Spectral Band — Green
Peak Wavelength — 530 nm
Peak Transmission — 54%
½ Bandpass — 67 nm
f/Number — 2.5

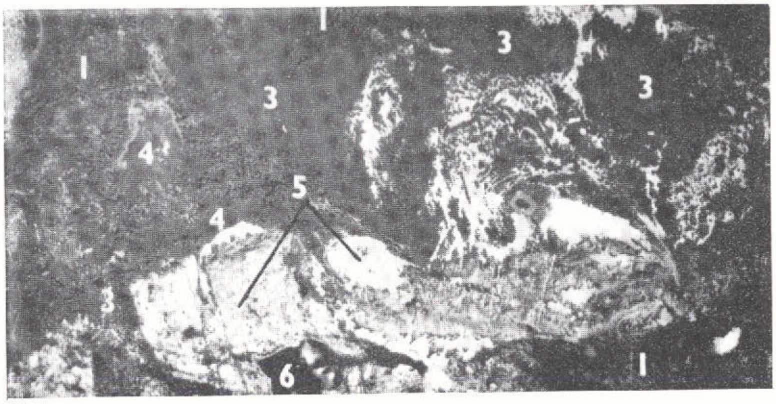

Figure 160d

Spectral Band — Blue
Peak Wavelength — 440 nm
Peak Transmission — 50%
½ Bandpass — 73 nm
f/Number — 8

Viewing Filters

Record	1	2	3	4
Filter	Red	Green	Blue	—
Saturation Level	100%	55%	90%	—

Evaluation of Multispectral Color Composite

— The color infrared simulation shown in Plate IXd was created by recombining Records #1, #2, and #3 as red, green, and blue respectively. All water areas are black. Bare soil and rock tend to a very desaturated blue, while brush and dry hardwoods, as well as meadow and riparian hardwoods, are a pinkish-red. Medium-to-high density conifers exist as a deep magenta surrounded by some blue soil showing through the trees.

APPLICATION — HYDROLOGY

Test Site Description

MONTAUK POINT, NEW YORK, lies at the easternmost tip of Long Island. A large amount of shoreline erosion and build-up occurs during the year due to storms and high winds. Waters on the north side of the point are rather turbid; most suspended materials consists of amorphous vegetative substances and silt.

Targets to be Detected

- Maximum depth to which submerged test panels are visible in turbid northern waters.
- Surface and submerged targets visible on same multispectral reconstituted image.

Flight Information

Date: 7 October 1967
Time: 1005 EDT
Altitude: 1000 feet
Weather: Clear
Film: EK # 2403
Filters: None, red, green, blue

Processing — Negative

Record	1	2	3	4
Gamma	1.7	1.8	1.6	1.5
Minimum Density	.23	.48	.32	.64

Processing — Positive

Record	1	2	3	4
Gamma	1.1	.7	.8	1.0
Minimum Density	.32	.12	.11	.12

Ground Truth — see figure 161a and c

a — yellow
b — blue
c — red
d — green
e — white
f — gray (64% reflectance)
g — gray (32% reflectance)
h — gray (16% reflectance)
I — gray (8% reflectance)
j — black

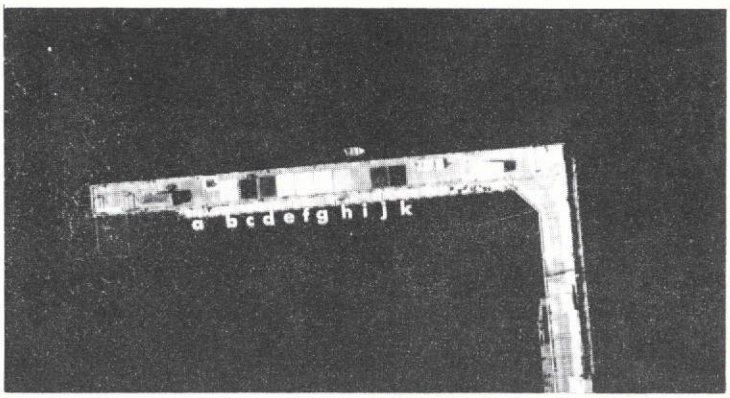

Figure 161a

Spectral Band — no filter
Peak Wavelength —
Peak Transmission —
½ Bandpass —
f/Number — 2.8

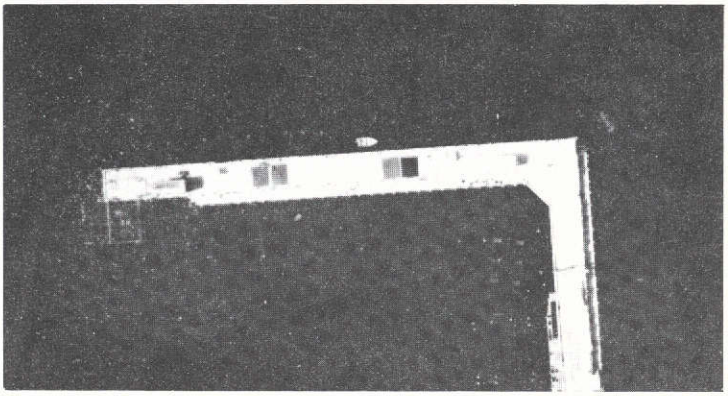

Figure 161b

Spectral Band — Blue
Peak Wavelength — 440 nm
Peak Transmission — 50%
½ Bandpass — 73 nm
f/Number — 2.8

Analysis of Black-and-White Positives

— The first image contains no filters and the positive exposure placed the highlights (the targets on the pier) on the straight line portion of the H and D curve. The readers's attention is called to the fact that target number A has the shadow of a building falling across one corner of it. Record #2, exposed through a broad band blue filter, was processed to place both the highlights and shadow areas (targets submerged twelve feet off the pier) on the straight line portion of the characteristic curve. This, however, was not successful; only the white panel of the submerged target array is visible. The remaining submerged targets are on the shoulder of the characteristic curve, while most of the surface targets lie along the toe portion of the curve. Only the red and green, as well as the deepest gray and black targets, lie on the straight line portion. Multispectral record #3, exposed through a green broad band filter, was processed in order to place the shadow areas on the straight line portion of the characteristic curve; hence most of the highlighted areas (the pier and the targets on it) lie along the toe of the curve. A comparison between this band and the first record which contains no filter indicates very clearly that one is required to process and expose the positive multispectral imagery such that the targets of interest, i.e., highlights or brightness, fall along the straight line portion without regard for other objects in the scene. The fourth band exposed through the broad band red filter was also processed as a compromise between the highlights and shadows. The result of doing this yields an image which has detail in neither region.

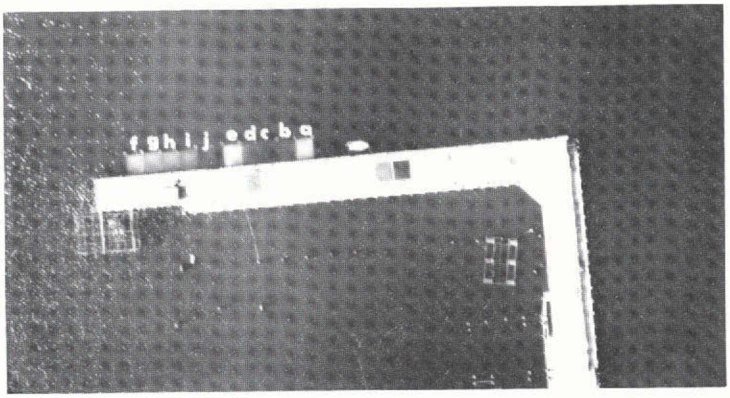

Figure 161c

Spectral Band — Green
Peak Wavelength — 530 nm
Peak Transmission — 54%
½ Bandpass — 67 nm
f/Number — 2.8

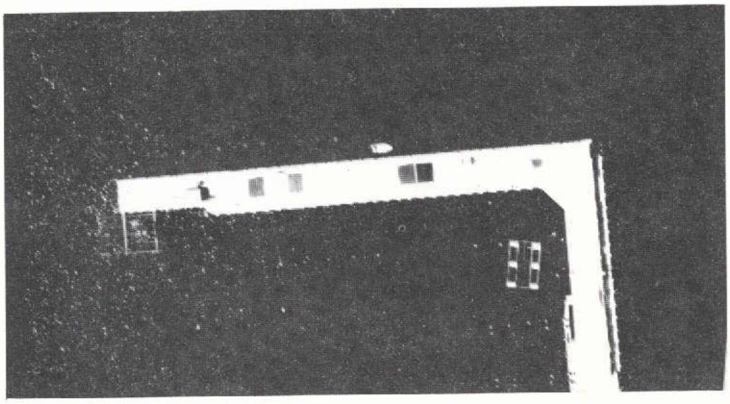

Figure 161d

Spectral Band — Red
Peak Wavelength — 700 nm
Peak Transmission — 50%
½ Bandpass — 110 nm
f/Number — 2.8

Viewing Filters

Record	1	2	3	4
Filter	—	Blue	Green	Red
Saturation Level	—	100%	50%	100%

Evaluation of Multispectral Color Composite

— The conventional true color multispectral rendition shown in Plate Xa was reproduced using Records #2, #3, and #4, the positives having been reprocessed only for the highlighted areas. One should note that the yellow target on the left side of the pier is covered by a shadow and the low-brightness green target appears black. Reprocessing for highlights has also caused the two darkest panels in the gray scale to be non-differentiable. Plate Xb shows the same multispectral records (as Plate Xa) reprocessed for the shadowed areas only. Here the submerged targets array can clearly be differentiated one from the other; however, the panels on the surface (in the highlights) are completely washed out. The isoluminous technique was applied to this frame and is shown in Plate Xc. Note that each of the color panels on the surface possesses its own color and the effect of the shadow falling across the yellow target has been completely eliminated in this rendition. Also the gray scales are of a somewhat uniform nature owing to the fact that all brightness differences in the scene have been eliminated. Only differences in the spectral distribution of the terrain objects are imaged as colors.

CHAPTER 13

MISSION PLANNING

To effectively collect multispectral photo imagery, it is important to plan the flight in a way which will satisfy the specified mission objectives and ensure that unnecessary labor and man-hours are not consumed by the project.

Once the intended use of the photography has been defined, it is necessary to determine the required characteristics of the imagery. The planning can then be carried forward by selecting from the available sources photographic equipment and materials which, in a practical and economic way, most nearly fulfill the requirements for the project under consideration. It is emphasized that a careful estimation of the time required to complete the flight mission is essential owing to the high costs which will be incurred.

While the requirements for both camera and film vary with the types of imagery desired, the exact interpretative task determines such factors as resolution and filters. The time of flight is selected to either minimize or maximize such factors as shadows and sunspot glare, while taking the best advantage of topography, existing horizontal and vertical control, and sun angle.

It must be noted that multispectral photography differs from conventional aerial color because it allows one to observe the subtle color differences existing in natural objects which are otherwise difficult to perceive. Hence, careful consideration has to be given to the determination of altitude and the differential exposures between camera bands.

This chapter reviews these and other variables to be considered in planning the flight. Reference is made to previous sections of the manual for details.

12.1 Camera

The choice of a specific aerial camera for remote sensing studies depends upon the following:

- Required ground resolution for interpretation
- Angular coverage per frame
- Flight altitude
- Overlap of imagery (60% for stereo viewing, 10% for mono viewing)
- Camera magazine capacity
- Types of imagery desired (black-and-white panchromatic, black-and-white infrared, color, color infrared, multispectral, etc.)
- Image motion compensation requirement
- Size of aircraft camera portal

If more than one type of imagery is required (say, color, color infrared, and multispectral), some modification of the camera mount may be necessary to fit this camera array into the opening of the plane. Careful design of any multiple camera mount is essential (it is a federal offense to drop anything from an aircraft!). When using multiple cameras for comparative studies of the imagery, it is desirable that all sensors have the same focal lengths and approximately the same resolution. To assure simultaneous exposure, all cameras should be fired off the same intervalometer.

Before the actual installation of the camera and accessories, it is important to ascertain if all components will perform with good engineering reliability during the flight mission. A faithfully executed check list of the equipment necessary will ensure that all the required parts are installed in the aircraft. A sample aerial camera installation list is given in Figure 162.

Prior to selecting a multispectral sensor for use in a photographic mission, one should be familiar with the necessary features of such a camera as described in Chapter 10. Particular attention should be given to the lens focal length and distortion characteristics since these will drastically affect the final image registration and the ultimate interpretation of the scene.

The following information should be furnished to the pilot and crew so that they understand the exact photo requirements and can economically perform the mission.

1. Purpose of the photography
2. Flight line layout
3. Film type
4. Filters to be used
5. Exposure data
6. Continuous flight strip requirement
7. Image motion tolerance
8. Scale
9. Sun angle tolerance
10. Forward overlap and side-lap
11. Sun spot tolerance
12. Haze tolerance
13. Allowable cloud cover
14. Direction of flight
15. Schedule

12.2 Films and Filters

There are several factors that affect the choice of filters and film: the end use (black-and-white, color, or color infrared for prints, transparencies, slides, or multispectral projection); environmental phenomena to be studied; probable presence of haze; flight altitude, and the average light of the terrain. Section 7.1 discusses film and filter selection in detail and Chapter 11 gives the specifications of candidate color and black-and-white films for aerial use.

Manufacturing tolerances for color negative and reversal emulsions are such that these films must often be used in conjunction with filters. These filters are either supplied with the films or are exactly specified so that a faithful reproduction of both tone and color balance results. *Do not* guess on the use of a filter for color films; if none is specified, it only indicates that the manufacturer does not consider it necessary. If, however, haze is apparent at low altitude, using a Kodak Skylight Filter (#1A) sometimes helps.

The selection of a set of filters for multispectral photography requires knowledge of the following parameters:

(a) The type of film to be used and its sensitometric characteristics.
(b) Reflectance characteristics of the scene to be photographed.
(c) The region of the spectrum which will best enhance anomalous features in the scene.

Project ____________________

Date ____________________ Checked By ____________________

Item and Description	Pre-Flight Tested	Installed in A/C
1. Camera Mount		
2. Camera		
3. Exposure Meter		
4. Camera Magazine		
5. Film Spools		
6. Camera Filters		
7. Cables		
8. Vacuum Pump Assembly		
9. Intervalometer		
10. Camera Control Panel		
11. Viewfinder		
12. Inverter		
13. Tool and Spare Parts Kit		
14. Camera Manual		
15. Lens Tissue		
16. Aerial Film as specified in flight plan and instructions		
17. Flight Plan		
18. Charts to Determine Exposure		

Figure 162

As explained in Section 7.1, it is important to consider the transmission of the filters selected in terms of the sensitivity of the film. Often neutral density filters are used in conjunction with spectral filters to assure accurate exposure of multispectral photography. This situation requires that the camera be calibrated prior to flight; that is, a pre-determination of the exposure ratio between each lens-filter combination of the multispectral camera is essential. Exposure tests can be performed by photographing a set of color, gray, and resolution targets from an elevated platform such as the roof of a building. Care must be taken that the panels or color targets are placed beyond the hyperfocal distance of the lens and that the focal length of the lens is changed if an infrared filter is used.

The primary purpose of pre-flight calibration is to assure that the resultant negative densities in each multispectral record will be on the straight line portion of the characteristic curve. Hence, a chart must be made to indicate the differential exposure required for each band taking into account the anticipated incident illumination at the time of flight.

12.3 Season and Weather Conditions

The season of the year must also be considered when planning a photo mission so that the most desirable ground cover conditions will occur when imagery is exposed. For example, in the case of agricultural studies it is important to determine what stage of crop growth development will yield the most information.

The principal weather factors affecting photographic results are: solar altitude, clouds, turbulence, and haze. Cloudless days occur when the relative humidity is low and the air is stable. Occasionally a photographic mission is aborted because of a cloud forecast that fails to materialize. How much of the available clear weather may be used depends on such specifications as minimum sun angle and what percentage of cloud and cloud shadow can be tolerated. As an example, in most tropical areas many days break clear and remain that way until cumulus clouds begin to build up, perhaps around 8 a.m. If the specifications require that the sun angle must be 30° or more and that the photographs be free of clouds or cloud shadows, acceptable photography is almost impossible to get in such areas.

Advance knowledge of anticipated weather conditions is invaluable for planning. Over a long period of years, the Weather Bureau has compiled statistics for the United States that are useful for determining optimum months or seasons for taking aerial photography. These data predict the number of days per month with 10% or less cloud cover that can be expected for any area. Care should be exercised in using average weather data recorded on the basis of percentage of cloud cover since such factors as haze, smoke, and fog are often not recorded. Rough air or turbulence bounces the aircraft causing image motion on the exposed film, thus reducing the final definition of the photographic images. When exposing photography at high altitudes, the loss in interpretability can become extremely serious owing to the small scale of the imagery.

12.4 Photographic Day

Many factors influence the time required for the operation of a flight mission. Among these are: weather expectancy, distance of the site from flying base, length and orientation of flight lines, physical limitations of personnel, flight weight, and the speed of the aircraft in ascent and at working altitude.

As the distance between the site of photography and the operating base is increased, the ratio of effective photographing time to travel time becomes increasingly unfavorable. Thus, it is of prime importance to base as close to the area as possible; not only is travel time minimized, but also the weather can be better evaluated. If the site area is far from the base, sometimes the weather at the site is good, while the base is fogged in.

In estimating flying time, the air speed of the aircraft at the particular working altitude should be reduced by the effect of probable winds and the time required to turn around between flight lines. It is often economical to orient the flight lines in one direction rather than another. In the case of a rectangular area, the strips should be laid out both ways to determine the most economical pattern from the standpoint of flying time and the number of photos involved. The determination of the flight day is dependent on the weather expectancy and on the nature of the discipline being studied. The upper and lower time limits of the flight day are generally specified by the solar illumination requirements taking into account the filter attenuation and the spectral sensitivity of the film. For example, in oceanographic studies where fine image detail is desired, it is essential to avoid the glittering patterns caused by the specular reflection from ripples and waves. Hence, photography taken at high solar angles is avoided. In the case of agricultural studies, noon time photography is preferred since a 90° sun angle causes a minimum of shadows to be imaged. If, however, the study is performed for crop height determination, then the photography must be obtained at a time other than noon so that by measuring the shadow length and the sun angle, the required mission objective can be achieved.

It should be apparent, then, that the correct time of flight for an aerial photographic mission can only be determined when the *specific* objectives of the project are known.

12.5 Summary

- Plan the photographic mission *only* after the objectives of the project are exactly specified.
- Choice of aerial sensor depends primarily upon final use of the imagery and the objects to be photographed.
- Checklists for pre-flight equipment tests and installation in aircraft are essential.
- Flight crew should be fully briefed on the project.
- Pre-flight calibration of camera (especially multispectral) is essential for correct exposure.
- Select hour of day and time of year for flight test based upon objects to be photographed and the mission objectives.

GLOSSARY

The following definitions are included for clarity and the reader's convenience.

Abridged spectrophotometry: measurement of spectral transmittance or reflectance at a limited number of wavelengths.

Absorption: conversion of radiant energy into other forms by passage through or by reflection from matter.

Achromatic color: color that does not elicit hue.

Additive color mixture: superimposition or other non-destructive combination of light of different chromaticities.

Additivity of luminance: luminance produced with a mixture of light from several sources is the sum of the luminances produced by the light from each of the sources acting separately.

Aperture: opening through which light passes.

Aperture stop: plane in optical system at which diaphragms of various sizes can be placed without varying size of field imaged.

Blackbody: radiator that completely absorbs all incident energy and reflects none.

Boundary of real colors: spectrum locus, together with the straight line joining its extremities.

Brightness: attribute of sensation by which an observer is aware of differences of luminance.

Calibration: measurement and specification of properties or performance of device, for subsequent use for subsidiary measurements.

Candle: unit of luminous intensity.

Chromatic aberration: imperfection of an image produced by variations of index of refraction of elements of an optical system.

Chromatic colors: colors eliciting hue.

Chromaticity: composite of dominant wavelength and purity.

Chromaticity coordinates: proportions of standard components required for color match, used as ordinate and abscissa to represent color in chromaticity diagram.

Chromaticity diagram: plane diagram formed by plotting one of the chromaticity coordinates against another.

C.I.E. chromaticity diagram: formed by plotting C.I.E. chromaticity coordinates.

C.I.E. source A: standard light source representative of quality of artificial illumination, recommended in 1931 by C.I.E.

C.I.E. source B: standard light source representative of direct sunlight at sea level, recommended in 1931 by C.I.E.

C.I.E. source C: standard light source representative of quality of daylight, recommended in 1931 by C.I.E.

Color dictionary: compilation of color names, usually illustrated with chromatic samples.

Color matching: procedure of adjusting a color mixture until all visually apparent differences from a sample color are eliminated.

Color-mixture curve: graph representing tri-stimulus value for unit flux of spectral energy, shown as a function of wavelength.

Color-mixture data: amounts of components required in three-color colorimeter to match various wavelengths.

Color reproduction: rendering of scene, by any process, in colors resembling the original.

Colorimeter: instrument designed for the direct measurement of color.

Colorimetric calculation: determination of color specifications by calculation from spectrophotometric data.

Colorimetric specification: statement of tri-stimulus values, or chromaticity and luminance, of a sample.

Colorimetry: technique of the measurement of color.

Complementary colors: pairs of samples of light that have complementary chromaticities and also the proper relative amounts of luminous flux to produce an achromatic mixture.

Dark current: current passed by photoelectric device when no radiant energy is incident on it.

Densitometer: instrument designed especially for measuring the densities of photographic deposits.

Desaturation: reduction of saturation, such as is caused by adaptation.

Directional reflectance: reflectance measured for a specified mode of irradiation and collection.

Dispersing system: device for separating various wavelengths of radiant energy.

Dominant wavelength: wavelength of spectrally pure energy that if mixed with white light would match a color.

Entrance slit: slit through which energy enters a spectroscopic instrument.

Equal-energy: spectral distribution characterized by equal flux per unit wavelength interval.

Filter: device with desired characteristics of selective absorption and optical homogeneity, used to modify the spectral composition of radiant energy.

Foot-candle: unit of illuminance equal to one lumen incident per square foot.

Gelatin filters: sheets of dyed gelatin used for optical purposes.

Hue: quality of sensation according to which an observer is aware of differences of wavelengths of radiant energy.

Illuminance: luminous flux incident per unit area of a surface.

Indirect colorimetry: computation of colorimetric specifications from spectrophotometric and psychophysical data.

Infrared: radiant energy with wavelengths somewhat longer than visible energy.

Integrating sphere: hollow sphere, with white interior, and small holes for admitting light and for observing the interior.

Interference filters: extremely thin alternate layers of metals and dielectrics that have very narrow passbands.

Inverse-square law: irradiance varies inversely as square of distance from a relatively small source.

Irradiance: radiant flux incident per unit area.

Lambert: unit of luminance.

Lambert's law: flux reflected per unit solid angle is proportional to cosine of angle measured from normal to surface.

Light: visual aspect of radiant energy.

Lovibond system: three sets of selectively absorbing glasses, used by superimposition to match and specify colors.

Luminous emittance: total luminous flux emitted per unit area of surface.

Luminous intensity: measure of luminous flux per unit solid angle emitted by a source.

Luminosity coefficient: fraction of each color-mixture curve that enters into the luminosity curve.

Magnesium oxide: white, highly diffusing pigment used as white standard for spectrophotometry.

Monochromator: dispersive device for isolation of narrow portions of the spectrum.

Munsell chroma: portion of Munsell notation that corresponds to saturation.

Munsell hue: portion of Munsell notation that corresponds to hue attribute of sensation.

Munsell system: system of classifying and designating attributes of opaque surface colors.

Munsell value: portion of Munsell notation that corresponds to lightness.

Negative component in color mixture: component that is mixed with the sample light in order to desaturate it sufficiently to obtain a match with a mixture of the other two components.

Neutral filter: filter that does not seriously alter the chromaticity of the light it transmits.

Nonselective filter: filter for which transmittance is substantially independent of wavelength.

Optical density: common logarithm of reciprocal of transmittance.

Perfect diffuser: surface that reflects in accordance with Lambert's law.

Photoelectric colorimeter: device employing photoelectric detector to measure three quantities related by linear combination to tri-stimulus values of any sample.

Photographic exposure: time of exposure multiplied by irradiance or illuminance.

Photographic material: material used for recording images by means of chemical change produced by light.

Photographic sensitometry: measurement of sensitivity of photographic materials and of relations between exposure and density of developed images.

Photomultiplier: photoemissive detector in which amplification by secondary emission is employed.

Primary: any one of three components used for production of extensive gamut of colors by additive mixtures.

Radiance: radiant intensity per unit projected area.

Radiant flux: rate of transfer of radiant energy.

Radiant reflectance: ratio of reflected radiant flux to incident flux.

Radiometry: measurement of radiant flux.

Reciprocity law: density of photographic image depends on the product of irradiance and time of exposure.

Saturation: quality of sensation by which an observer is aware of different purities of any one dominant wavelength.

Selected-ordinate method: numerical integration using unequal intervals of integration variable, so as to eliminate multiplications in determination of contribution of each interval.

Selective absorption: absorption of different proportions of different wavelengths.

Sensitivity: capacity to detect small amounts of radiant energy.

Skylight: components of sunlight that are scattered by the atmosphere.

Specification of color: statement of amounts of three components necessary to match the color.

Spectrophotometer: device for the measurement of spectral transmittance, spectral reflectance, or relative spectral emittance.

Spectrophotometric curve: graph of reflectance or transmittance versus wavelength.

Spectroradiometer: device for the measurement of spectral distribution of radiant energy.

Spectrum: spatial arrangement of components of radiant energy in order of their wavelengths.

Spectrum color: color represented by any point on the spectrum locus.

Spectrum locus: curve connecting points in chromaticity diagram that represent various wavelengths of the spectrum.

Specular density: logarithm of the reciprocal of specular transmittance.

Specular reflection: reflected beam which leaves surface at an angle equal to the incident angle.

Steradian: unit of solid angle, subtended at center of sphere of one meter radius by one square meter area on that sphere.

Three-color colorimeter: colorimeter in which colors are matched by mixtures of three colors of invariable chromaticity but variable luminance.

Three-filter colorimeter: additive colorimeter employing three filters to produce mixture components.

Transformation of color mixture data: application of transformation equations to derive color-mixture data for desired set of primaries from known color-mixture data for other primaries.

Trichromatic colorimetry: measurement of color in terms of mixtures of three prescribed chromaticities.

Tristimulus value: amount of a component necessary in a three-color mixture matching a sample color.

Ultraviolet: radiant energy having wavelengths less than about 400 nm.

Wavelength: quantitative specification of kinds of radiant energy.

Weighted-ordinate method: numerical integration of product at equal intervals of variable.

White: color name, most usually applied to opaque, highly reflecting, diffusing objects.

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