GPO PRICE $ ______

CFSTI PRICE(S) $ ______

Hard copy (HC) 3.00

Microfiche (MF) ______

ff 653 July 65

[redacted]

SCIENCE ENGINEERING RESEARCH GROUP

FACILITY FORM

N68-38166 (ACCESSION NUMBER)	(THRU)
153 (PAGES)	0 (CODE)
CR-92360 (NASA CR OR TMX OR AD NUMBER)	14 (CATEGORY)

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SERG-TR-04

PRECISION MULTISPECTRAL PHOTOGRAPHY FOR EARTH RESOURCES APPLICATIONS

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Prepared for the National Aeronautics and Space Administration under Contract Number NAS 9-7291

Long Island University
Science Engineering Research Group

Technical Report SERG-TR-04
1 September 1968

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SECTION

INTRODUCTION

This report presents the results of an experiment which was conducted during the summer 1967 to evaluate the usefulness of the remote sensing technology of multiband color photography for earth resources applications of agriculture, forestry, geography and geology.

The four lens multispectral camera was used to obtain multiband photography of each test site. Photo interpretation and colorimetric image analysis were performed using the companion additive color viewer. Simultaneous Aero Ektachrome and Aero Ektachrome Infrared photography was also taken during all phases of the experiment. In order to facilitate the colorimetric comparison of the characteristics of both additive and subtractive color images and because reliable spectral signature data was generally unavailable, the spectral bands used in the multispectral camera were chosen to match the bands of the spectrum to which the color films were sensitive.

Throughout the experiment extensive ground control was used which included: grey scale and color targets, measurements of the spectral intensity and distribution of the incident solar radiation; spectroradiometric measurements of the solar energy reflected by ground targets as well as selected environmental objects on vivo; colorimetric measurements of color and grey scale target-panels and selected ground objects.

The experiment was conducted at flight altitudes ranging from 1000 feet to 30,000 feet above sea level. Primary emphasis was given to the higher altitudes to place the largest possible column of air between the ground and camera so that atmospheric effects would be included in the imagery obtained.

1.1 Fundamental Problems

Prior to performance of the experiment, three fundamental problems were distinguished as being of critical importance in obtaining precision multiband photography. These problems are not unique to photographic sensors and in fact generally apply to any remote sensing technique in the .26 to 3 micron part of the electromagnetic spectrum where reflection rather than emission phenomenon is encountered.

The first problem relates to the lack of accuracy and precision in the structure of the image due to instrumentation errors. These arise from three sources: (1) sensor errors in formation of the spectral image, (2) photographic errors in transforming the image energy to density in the photograph subsequently used in data reduction, (3) errors in the viewing apparatus which constructs the color image for qualitative viewing by the interpreter and for quantitative colorimetric analysis.

Psycho-physiological variables in viewing color images are not treated in this report although such considerations are critical in the qualitative interpretation of aerial photography. All the data presented herein are in terms of analytical color measurement and thus psychological variables such as simultaneous contrast enhancement do not appear in this analysis.

The second problem centers on the environment. In this case three variables are distinguished: (1) the intensity and spectral distribution of the solar illuminant (a fractional part of which is reflected into the camera and thus forms the image) changes as a function of the solar angle, atmospheric conditions, secondary reflectance and the relative composition of direct sunlight and diffuse skylight, (2) the en vivo spectral reflectance of surface objects (crops, soils, trees, etc.) which is known to vary dynamically at least as a function of the non-lambertian (directional) spectral reflectance of objects due to their orientation with respect to both the angle of incidence and angle of reflection as well as due to temporal changes in the absorption and transmission of the object itself, (3) the atmosphere between the object and the sensor which scatters and absorbs the radiation reflected by the object.

The third and perhaps most important problem is the physical relationship between reflectance spectra and color. Given a particular spectra and a set of taking-viewing filters which establish a color space, a unique color will be produced. That is, the reflectance spectra of the object relates to one and only one color, thus defined, regardless whether additive or subtractive color principles are used. However, the inverse is not true. Given a color (in any predefined color space), it can not be uniquely described to a particular spectra. An infinite number of spectral reflectance curves can produce an identical color.

One of the primary purposes of multispectral color aerial photography is to circumvent this physical law which relates spectra to color. This is accomplised by choosing taking filters based upon analysis of the on vivo spectral reflectance characteristics of objects and then creating a false color space which maximizes the apparent color difference between the objects.

1.2 Objectives of the Experiment

The five primary objectives of the experiment were as follows:

- evaluation of the accuracy of the chromatic characteristics of the image produced using multiband photographic techniques. This accuracy being achieved by adjustment of the additive color image which in turn alters the effects of variations in solar illuminant and the effects of the atmosphere.

- to evaluate the uniqueness of color signatures obtained with a priori defined taking filters using color space formation capabilities of the viewer.

-to compare the characteristics of images formed by multispectral additive color photography with conventional subtractive color films sensitive to both the visible and infrared radiation.

-to measure the environmental variables which affect this technique of remote sensing and to correlate them with the imagery.

-to obtain reflectance spectra of objects of significant interest to the earth resources disciplines and thus indicate the optimal spectral bands for taking multiband photography which allow maximization of the difference in color between objects.

1.3 General Procedures

The general procedures used throughout the experiment can now be given with reference to the objectives and the problems associated with the experiment.

The multispectral camera was equipped with four filters which passed only the blue, green, red and infrared spectral bands. The film used was "black and white", infrared sensitive film (Kodak #5424). Two auxiliary K-24 cameras, each with lenses identical to the multispectral camera, were loaded with Aero Ektachrome (#8442) and Aero Ektachrome Infrared (#8443) film. The three cameras were aligned in a common mount such that the optical axes were parallel. All cameras were activated by a common intervalometer so that exposures were taken at the same time (within the shutter tolerances of the three cameras). A range of exposures was used in both the multispectral camera and color cameras to insure the best possible exposure of the ground scene on the film.

The negative infrared film was processed in a continuous Versamat processor using D-19 developer. Sensitometric control was maintained throughout the processing. In general, a medium to high contrast was obtained on the negative although this varied depending on the conditions encountered at a particular test site. Positive transparencies were obtained by duplicating on Kodak #5427 film using a Niagra printer and Versamat processed in MX 641-1 developer. Sensitometric control was, of course, maintained. Color films were processed using the rewind method, control strips being used to insure the best possible development with in the state of the technology.

The positive images were placed in the additive color viewer. Numerous color spaces were experimentally formed in order to establish those which gave the color differentiation which the cognizant earth scientist considered best for his application. The color of ground targets and significant environmental images were measured using a colorimeter. This data was compared with ground measurements made at the time the photography was taken. A similar analysis was performed for subtractive color films.

Environmental measurements of the incident solar energy and spectral reflectance were reduced to common illumination condition and analyzed as to differences in spectral reflectance. Similar analysis was performed comparing the spectrophotometric total diffuse reflectance measurements of surface targets and the field spectroradiometric data.

1.4 Outline of the Report

The following section of this report describes the remote sensing instrumentation used in the experiment. This discussion includes details on the camera and viewer design as well as some of the basic principles of additive color theory.

Section 3 presents theoretical and empirical considerations on the relationships between the characteristics of the black and white multiband image and the resulting additive color image. Empirical examples of variations in color with change in the characteristic curve are included.

Section 4 discusses the environmental measurements and instrumentation that was used. Basic data on variations in intensity and spectral distribution of solar energy, reflectance of standard ground targets and their color under solar illumination are presented illustrating the significant parameters affecting multiband techniques.

Section 5 presents the results achieved at each test site. It includes quantative color comparison of ground targets and objects of significant interest on both multispectral color and on subtractive color films.

Section 6 presents the conclusions which result from the experiment and implications for future experiments and the design of improved instrumentation.

SECTION 2

INSTRUMENTION, DATA ANALYSIS EQUIPMENT AND TECHNIQUES

The equipment used in the experiment consisted of the four lens multispectral camera and associated color viewer system conceived and designed by the authors and manufactured by the Fairchild Camera and Instrument Corporation. Two auxillary cameras of the K-24 type, manufactured by Eastman Kodak Co., were used to obtain supplementary color photography. The multispectral camera utilized "black and white" infrared Aerographic film (Kodak #5424) and was equipped with combination absorption and interference filters covering the following four spectral bands:

Band 1- Blue (395-510 nanometers)

Band 2- Green (480-590 nanometers)

Band 3- Red (585-715 nanometers)

Band 4- Infrared (700-900 nanometers)

The log sensitivity of the film as well as the transmission of the filters and camera lenses as a function of wavelength are shown in Figure 1. The reader should note that the three filters used for the visible spectral bands were specially designed to block the transmission of all infrared radiation.

For this particular experiment little en vivo spectral reflectance data was available for targets of interest to the earth resources disciplines. Consequently, the spectral bands used in the multispectral camera were chosen to approximate the spectral sensitivity of conventional color and infrared color films.

The two auxillary cameras utilized Aero-Ektachrome (#8442) and Aero-

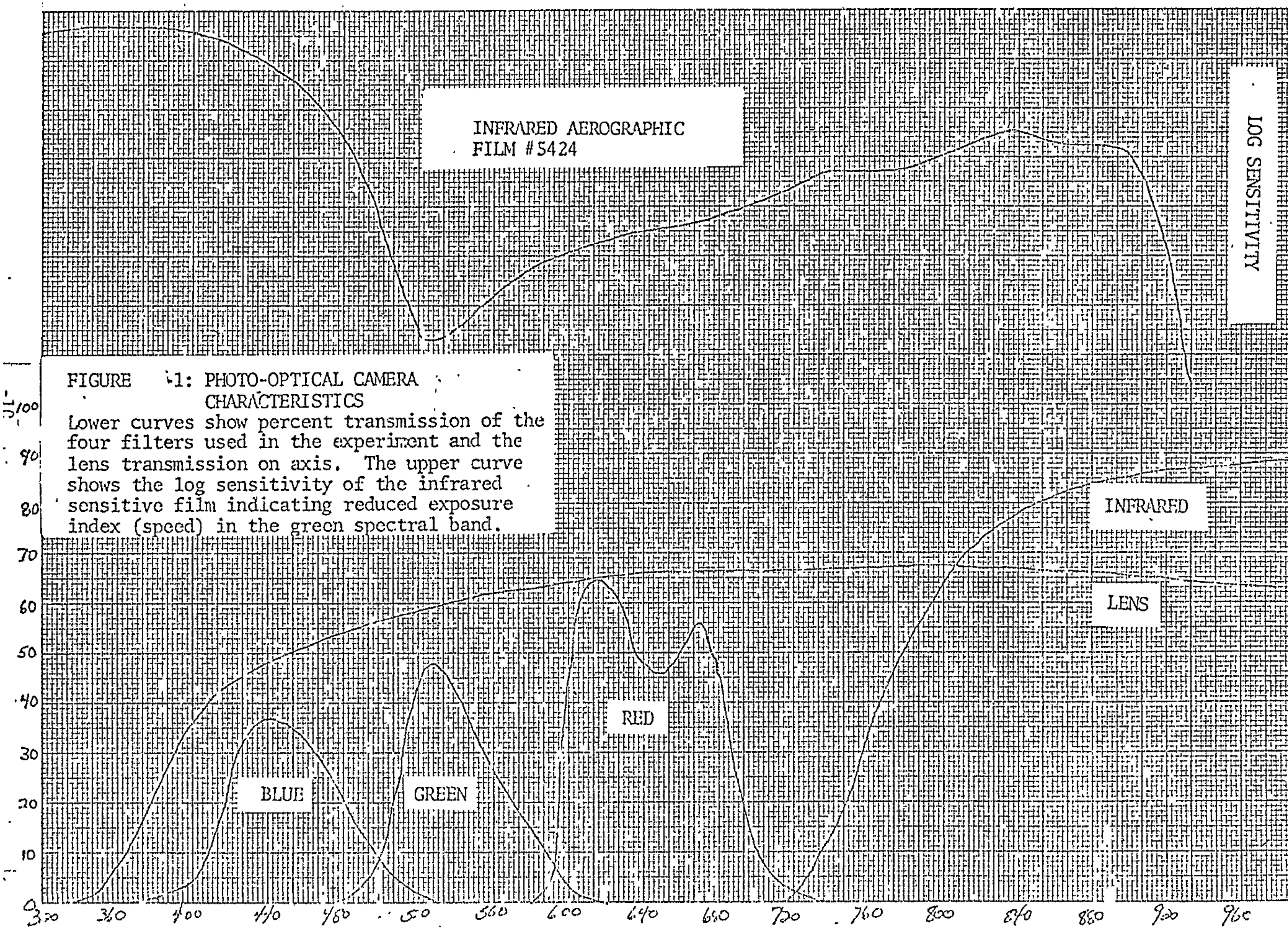


FIGURE 1: PHOTO-OPTICAL CAMERA CHARACTERISTICS

Lower curves show percent transmission of the four filters used in the experiment and the lens transmission on axis. The upper curve shows the log sensitivity of the infrared sensitive film indicating reduced exposure index (speed) in the green spectral band.

Ektachrome Infrared (8443) color reversal emulsions. The spectral bands to which these films are (nominally) sensitive are as follows (for a sensitivity of 1):

Auxillary camera #1 (no filter)	Aero Ektachrome	"blue band"(360-510nm)
		"green band"(360-590nm)
		"red band"(470-690nm)
Auxillary camera #2 (Wratten 12 filter)	Aero Ektachrome Infrared	
		"green band"(500-600nm)
		"red band" (500-700nm)
		"infrared band" (580-890nm)

Analysis of the multispectral photography taken during the experiment was performed by using the companion viewer. This apparatus uses additive color principles to project a single composite color rendition of the images associated with the four spectral bands. The presence of slight density differences of the same image among the four spectral photographs results in a color in the composite rendition projected on the screen of the viewer. This device also incorporates brightness, hue and desaturation controls which give the operator the capability to manipulate the relative color of screen images in order to emphasize s subtle chromatic differences for photo-interpretative purposes.

2.1 Multispectral Camera

The four lens multispectral camera shown in Figure 2 is a frame

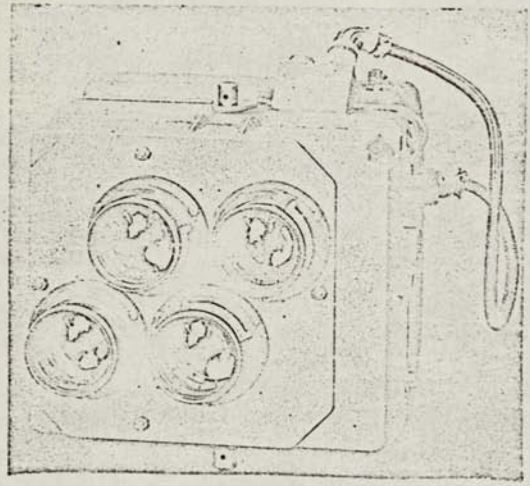


FIGURE 2: MULTISPECTRAL CAMERA

Simultaneous spectral photography in spatially identical formats can be taken in any four spectral bands between 360 and 900 nanometers with the camera and associated control equipment.

type aerial sensor. It has been designed so that the photographic emulsion is exposed through four individual lenses each one of which can be filtered to cover any desired wavelength band above 360 nanometers. At wavelengths less than this, radiation is absorbed by the glass elements of the lens. The upper limit of the radiation sensed is established by the film emulsion between 900 and 1000 nanometers.

The camera is designed primarily to use a unitary film configuration in which four exposures are obtained on one piece of 9 1/2 inch wide film. However, the capability to use four different films each 2 1/4 inches wide has been incorporated in the camera design. The magazine capacity is 400 feet of 5.2 mill thickness film. The camera has been equipped with an image motion compensation (IMC) device to allow use of long exposure times at low altitudes and high aircraft velocities without causing image blur. A single focal plane shutter is employed to expose all four photographs at precisely the same instant of time. This feature assists in accurate registration of multiple images in the viewer by eliminating image displacement between the four images which might result from aircraft angular motion during exposure.

2.1.1 Opto-Mechanical Design of The Camera

The multispectral camera-viewer system was designed to specific tolerances in order to eliminate many of the registration problems associated with the data reduction of multiband type of photography. Most multispectral systems have not proven to be a practical technique, nor are they employed on a continuing basis, principally because of the time and effort required to register or otherwise analyze the multiple frames of photography. The precise design of the multispectral camera circumvents these difficulties by producing a set of four photographs, matched in scale and yielding identical coverage with exact registration of the imagery on a single unitary film.

The variation of the amount of light bending as a function of wavelength is dependent upon the configuration and nature of the transmitting material. It is known as optical dispersion, shorter wavelengths being generally bent more than longer wavelengths. A lens is analogous to a prism in which incident parallel light will be bent more upon emergence if it is blue and less if it is red. For purposes of uniform multispectral photographic scale, this dependency of focal length with wavelength requires the use of lenses which are matched in focal length throughout the spectrum. This match of focal length for all wavelengths permits the mating of any desired taking filter with any lens. Not only must the focal lengths of the four multispectral lenses be invariant with respect to wavelength throughout the spectrum used, but the physical considerations of the actual flange focal distance (the distance from the flange of the lens to the focal plane) affects the accuracy of scale matching which can be obtained by the camera. For the same resolution criteria, the focal plane of each filtered light bundle must lie within the nominal depth of focus of all four lenses as shown in Figure 3. Given a resolution requirement of 45 l/mm on a single multispectral record at f/2.5, one may compute the total depth of focus from:

total depth of focus = 2 (d) (f)

where d = the circle of confustion

f = the f number of the lens.

For the conditions cited above, the depth of focus is .0045 inch.

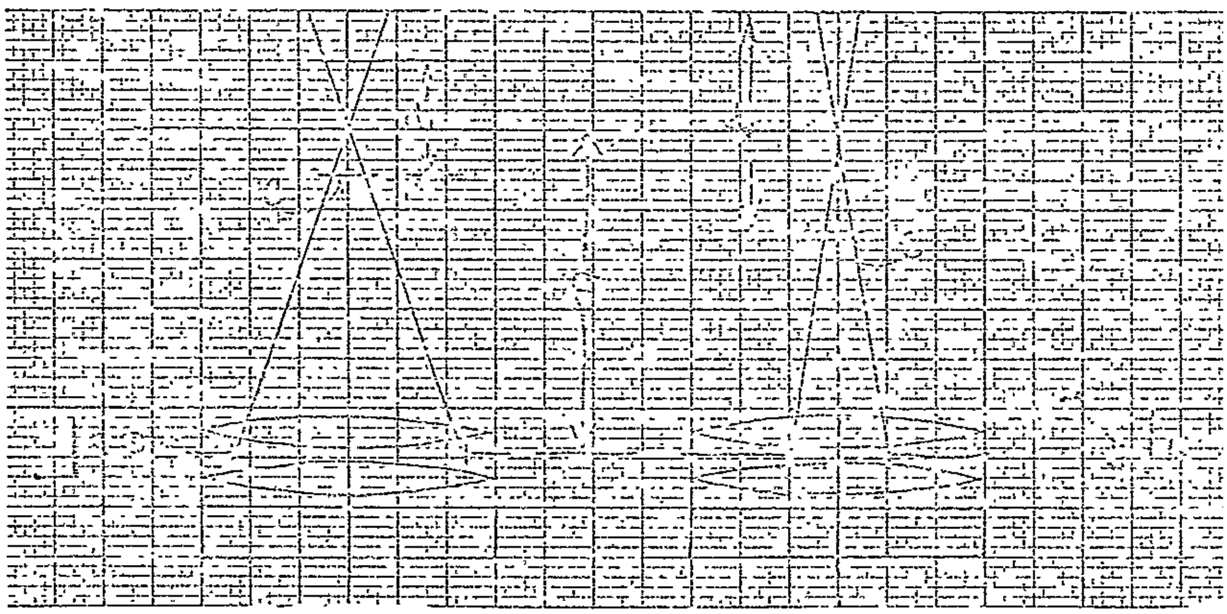


FIGURE 3

DEPTH OF FOCUS INCREASES WITH INCREASING f/NUMBER. THE FILM MUST LIE WITHIN THE DEPTH OF FOCUS OF ALL LENSES.

Another aberration which influences the resultant photographic scale is the inherent distortion which exists in every lens across its field. In order that the imagery be well registered, it is required that the distortion characteristics of each lens be well matched. This does not poses of alignment. In the alignment process, a jig was made which would hold the body of the camera and the focal plane firmly in place because the vacumn platten is removed for this adjustment. A travelling microscope with a filar eyepiece is mounted on the jig so that precise measurement in the X and Y directions is possible to achieve the desired alignment.

The multispectral camera incorporates a film guide mechanism which insures that the film will transport accurately through the camera. A similar guide mechanism has been designed into the associated viewer so that the film will transport with respect to the projection system achieving accurate registration. Such transport accuracy insures the photo-interpreter of good registration throughout the roll of film. It should be noted, however, that manual registration of the first frame of photography is required to eliminate the effects of film shrinkage along the width of the film.

In order that the photography obtained in each of the four spectral bands be exposed at exactly the same instant of time, the conventional between-the-lens shutters are not employed in the camera. Instead, a single focal plane shutter was designed with four slits (one for each lens) to eliminate the conventional misregistration problems caused by aircraft angular motion which exists when the photography is not exposed simultaneously.

2.1.2 Exposure Control and Ground Tests

Photographic emulsions including panchromatic do not have an equal response to radiation throughout the spectrum and consequently exhibit a varying sensitivity as a function of wavelength. Since the taking filters in the camera transmit different wavelengths and a fixed exposure time is used, consideration must be given to the required exposure control over each spectral band. With an equal exposure time as well as varying values of film sensitivity and energy transmitted in each spectral band, an object of uniform spectral brightness will be recorded as a different density in each spectral photograph. In order to eliminate this error and make the spectral photography have a density proportional to the energy source, a ground calibration must be performed for each set of taking filters and film type to be employed.

The relative exposure through the selected multispectral camera filters is calibrated in the following way. A set of grey scale panels is set up under daylight illumination together with a set of resolution targets. The filters and film to be used in the test are installed in the camera and the ground targets are photographed at all possible f/numbers. The spectral ditribution and intensity of the solar illuminant is also measured simultaneously and the test is only considered valid if the total spectral energy is within plus or minus 5 percent of the distribution of Standard Sunlight (Luminance C) in each band. The film is precision processed under sensitometric control and is then examined for that value of f/number of each lens which will yeild the same density values of the ground target. That spectral photo which requires the smallest value of f/number is then used as a standard. Each of the remaining lenses are then corrected with the use of neutral density filters so that the same f/number on each of the lenses will now render the grey scale ground panels as equal in density. These neutral density filters are then permenently installed in front of the lenses and no differential exposure time is required for each of the photos. In flight, therefore, the photographer need only change all the f/numbers by the same amount to vary the exposure. This assures that a grey scale target on the ground, under standard illumination, will appear the same density on the set of four spectral photographs.

2.1.3 Multispectral Filtration

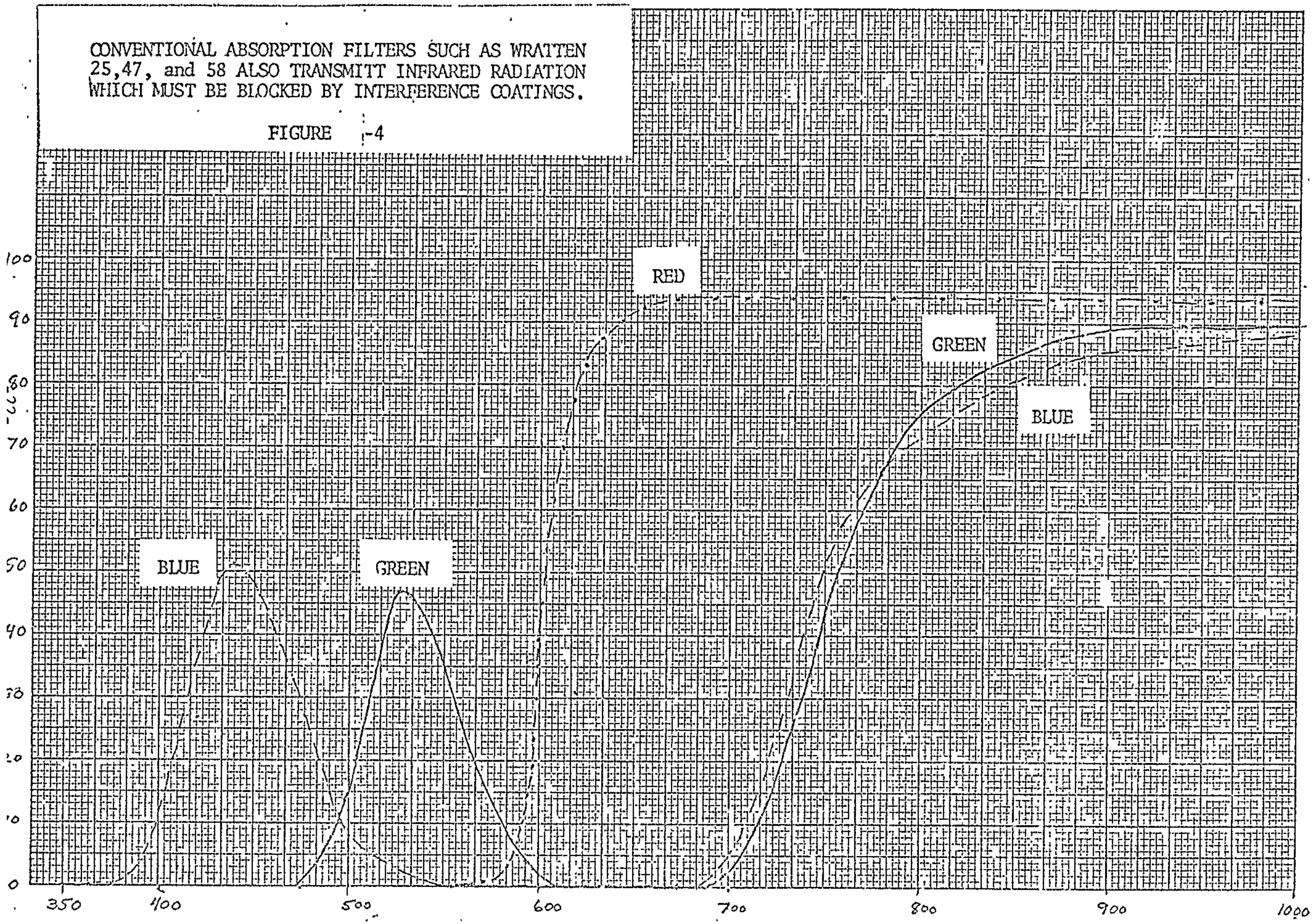
A spectral filter may be thought of as a window through which energy passes, the transmission being a function of the wavelength of the radiation. A desirable filter band is one in which the radiant power to "target signals" is different from that of "back-ground signals". The determination of a good filter is made difficult by the fact that the spectral distributions of the solar energy reflected by the target and background are either (1) unknown, (2) are very similar, (3) change dynamically with environmental conditions.

The multispectral camera discussed herein, employs a set of transmission filters to isolate four regions of the visible-near infrared spectrum from approximately 360 to 1000 nanometers. Ideally, choice of filters might be based upon the spectral reflectivity of the geophysical phenomenon which is to be detected as well as the environmental background in which such a target is embedded. As the phenomenon of interest becomes more general and the type of backgrounds in which the targets are embedded become more varied, it is the current procedure to select a set of taking filters which are broadband in nature. That is, four filters which together cover the entire .36 to 1 micron region and which have reasonably high transmission properties. Wide band filters have been used to date when the number of items to be detected from the same photographic experiment are extensive. Conversly, as the number of targets to be detected during one experiment is decreased and when these targets exist in similar environmental areas, one would reasonably expect that narrow band filtration would give better results.

Broadband filters are generally of the absorption type although frequently (as in the case of this experiment) interference coatings are also added to block the transmission of infrared radiation. However, as the mission objectives become more specific and detailed spectral signatures of targets of interest are established, significant improvement in performance can be obtained by using the multi-layer or interference type filter. These filters may be designed and manufactured so that their maximum transmittance exists at any chosen wavelength. However, care must be taken that there exists sufficient spectral transmission to allow for good exposure on the photographic emulsion used.

Several problems are associated with the use of the multi-layer or interference type of filters. The first difficulty consists of a general shift in the peak bandpass of the filter as a function of field angle since the optical thickness of the thin film deposit varies as the angle of incidence is increased, resulting in a shift towards the shorter wavelengths. The second diffiuclty enountered with the use of multi-layered filters consists of a shift to the longer wavelength region when the temperature of the filter is increased and a shift to the shorter wavelength exists when the filter temperature is decreased. For the most part the wavelength shift of an interference filter is essentially a linear function of the filter temperature.

A typical problem in multispectral photography which employs absorption filters in the wavelength region from 360 to 1000 nanometers, is the transmission of infrared radiation. This can be seen from Figure 4. As a result when one uses conventional infrared emulsions (such as EK 5424) in conjunction with an absorption type filter, the photographic emulsion will respond to not only that wavelength region of interest but also to the infrared radiation which is also transmitted. To eliminate such difficulties most of the broadband filters which exhibit such a property can incorporate an interference "blocking" coating to eliminate any transmission outside of the desired band.



CONVENTIONAL ABSORPTION FILTERS SUCH AS WRATTEN 25,47, and 58 ALSO TRANSMITT INFRARED RADIATION WHICH MUST BE BLOCKED BY INTERFERENCE COATINGS.

FIGURE -4

When considering the total transmission of the incident radiation impinging on to the photographic emulsion through the multispectral system, one must also consider the spectral transmission characteristics of the taking lens. The on axis spectral distribution of light transmittance for the Aero-Ektar lens used in the multispectral camera was shown in Figure 1. Off axis the shape of this curve remains the same but is reduced in amplitude. This reduction in energy as a function of field angle of the lens (often called $Cosine^4$ fall-off or vignetting) should be corrected to obtain accurate spectral photography. This is accomplished using an anti-vignetting filter to reduce the on axis transmission and has the effect of increasing the T stop of the lens. This practice restricts the use of the lens to a shorter photographic day since more energy must enter the lens (on axis) to produce the same exposure as would be obtained without such a filter.

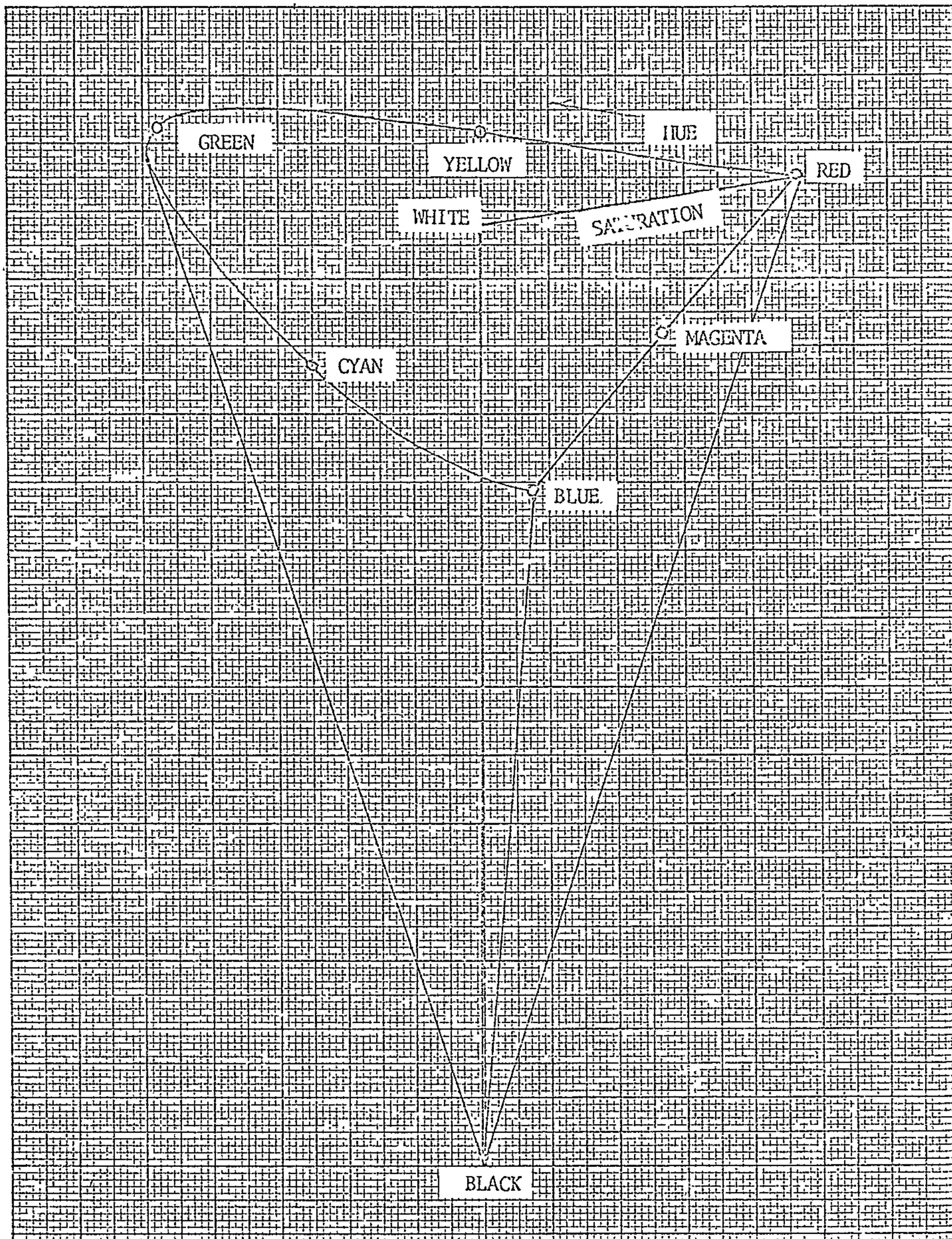
2.2 Additive Color Techniques

Each of the four spectral negatives, which together comprise the set of multispectral photographs, is taken at the same instant by four matched lenses. Since the optical axes of all the lenses are normal to the film plane, four spatially identical negatives are produced. Thus, all the images appear in identical coordinate positions as measured from the principal point of each negative (the intersection of the optical axis with the film plane). When the film is processed and viewed on a light table, the set of multispectral negatives appear to be identical except that the densities of the same image may differ between them. This difference is caused in part by the selective spectral reflectance of ground objects, a fact which, in the visible spectrum, accounts for their apparent color.

Color is an effective means of discriminating density differences between similar images which appear on sets of multispectral negatives. This is done using additive color techniques first demonstrated by Clerk Maxwell over 100 years ago. By projecting positives of each spectral negative on to a screen in such a fashion that one is registered upon the other (using a different colored primary light source for each), a composite color rendition of the ground scene is formed.

Color may be defined as that conscious sensation which is exhibited when light of a specific spectral energy distribution enters the eye. It has been experimentally shown that differences in this energy distribution, which cause variations in the observed response of the eye, may be described in terms of three distinct psycophysical variables. The first is hue which is basically that quality of color which leads to the definition of an object as being red, or green, or yellow, etc. As white light is dispersed by a prism, it is broken up into a multitude of hues each one of which may be related to a corresponding value of wavelength producing a dominant wavelength which in turn enters the eye to produce the sensation of hue. Saturation, the second quality of color, is described as the amount of white in a given hue. It may be also considered as the concentration of the color. It is the difference between red and pink. As the amount of saturation in a color decreases, it approaches pure white. Brightness, which is the third variable of color, is described as the amount of visible energy contained in a certain hue which is saturated to a specific value. For example, the color royal blue, is identical to the color navy blue except that navy blue has a lower brightness value.

It has been estimated that the human eye can differentiate between 7,500,000 and 10,000,000 color differences over its sensitivity range. Thus, it is impossible for scientific purposes to use subjective terms for the unambiguous description of a color. The human eye is a relatively insensitive instrument when used to uniquely describe the appearance of an object with respect to its color. It is for this reason that a mathematical conception of the three variables defined above be employed to describe that response (by the eye or a recording instrument) to the stimulus known as color. We may envision these three variables of hue, brightness and saturation with the aid of a three dimensional color solid shown in Figure 5. It consists essentially of a solid cone standing on its apex with the hue positioned around the periphery of the solid, the saturation existing somewhere along the line connecting the center or white point with the hue of interest and the brightness varying with

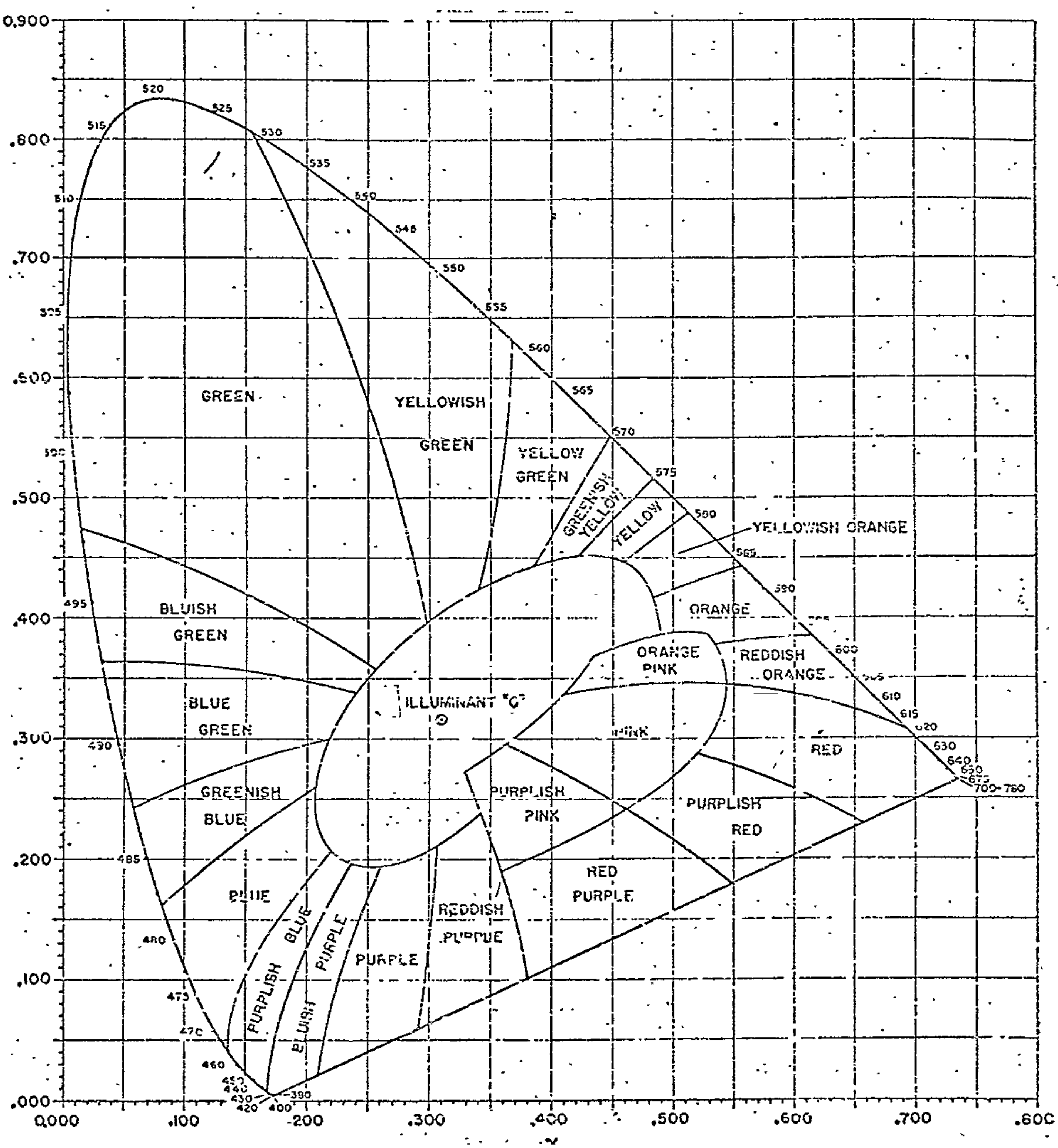


THREE DIMENSIONAL COLOR SOLID INDICATING THE THREE VARIABLES OF HUE, BRIGHTNESS AND SATURATION.

FIGURE 5

position along the vertical axis. More precisely, the color solid is not a cone, but rather a rounded triangle. A horizontal slice through this solid, perpendicular to the brightness axes is known as a chromaticity diagram and is shown in Figure 6.in which certain colors have been identified. In order to pictorially describe the exact hue, brightness and saturation levels of a color it is first necessary to determine the brightness level, place an orthogonal plane through the color solid at that level and determine the hue and saturation in this plane.

It should be emphasized that the mathematical study and description of color, which is known as colorimetry, only indicates the specific values of hue, brightness and saturation which are being measured and not the energy distribution of the color as a function of wavelength. The theory of colorimetry is based upon the concept that any color which exists in reality can be matched by some combination of three given colors or primaries. However, it has been demonstrated that there does not exist a single set of primary filters which can yield every color. In multispectral photography, a judicious choice of (camera) filters must be selected depending upon the spectral reflectance and the general domain of colors which are to be reproduced. For the reproduction of true color using additive methods, the primary colors shown in Figure 7, which are red, green and blue, have been selected for two distinct reasons. First, it is desirable to maximize the area of the inscribed triangle since only those colors within that triangle may be reproduced by a com-



FIGURE

THE INTERNATIONAL STANDARD CHROMATICITY DIAGRAM OF THE C.I.E. SYSTEM bination of the three primaries. Secondly, the triangle is positioned so that one side lies close to the locus of the pure spectrum of the green-yellow-red colors since these colors appear in nature but the pure spectrum colors in the cyan portion of the chromaticity diagram do not.

The trichromatic system of color definition is a calculation of the fractional components of spectrally defined red and green primaries (referred to in colorimetry as the tristimulus values) for a given color. They are designated as x and y respectively and are known as trichromatic coefficients. These represent the percentage of standard red and green primaries required to produce a hue and saturation match to the color. A third value, Y, represents the luminance or brightness level of the color. The standard chromaticity diagram mentioned above is a plot of the color in terms of x and y. The dominant wavelength of a color is determined by the intercept of the spectrum locus with the line which connects the illuminant point (the white point) and the color itself. The relative distance between the white point and the color and, the color and the spectrum locus is the saturation.

In multispectral photography, colorimetric measurement is a useful tool to remove any anomolies associated with the visual response of the observer. The persceptibility of differences in the C.I.E. chromaticity diagram are shown in Figure 8. Generally, colors which appear identical on a viewer secreen to an observer, will not exhibit the same

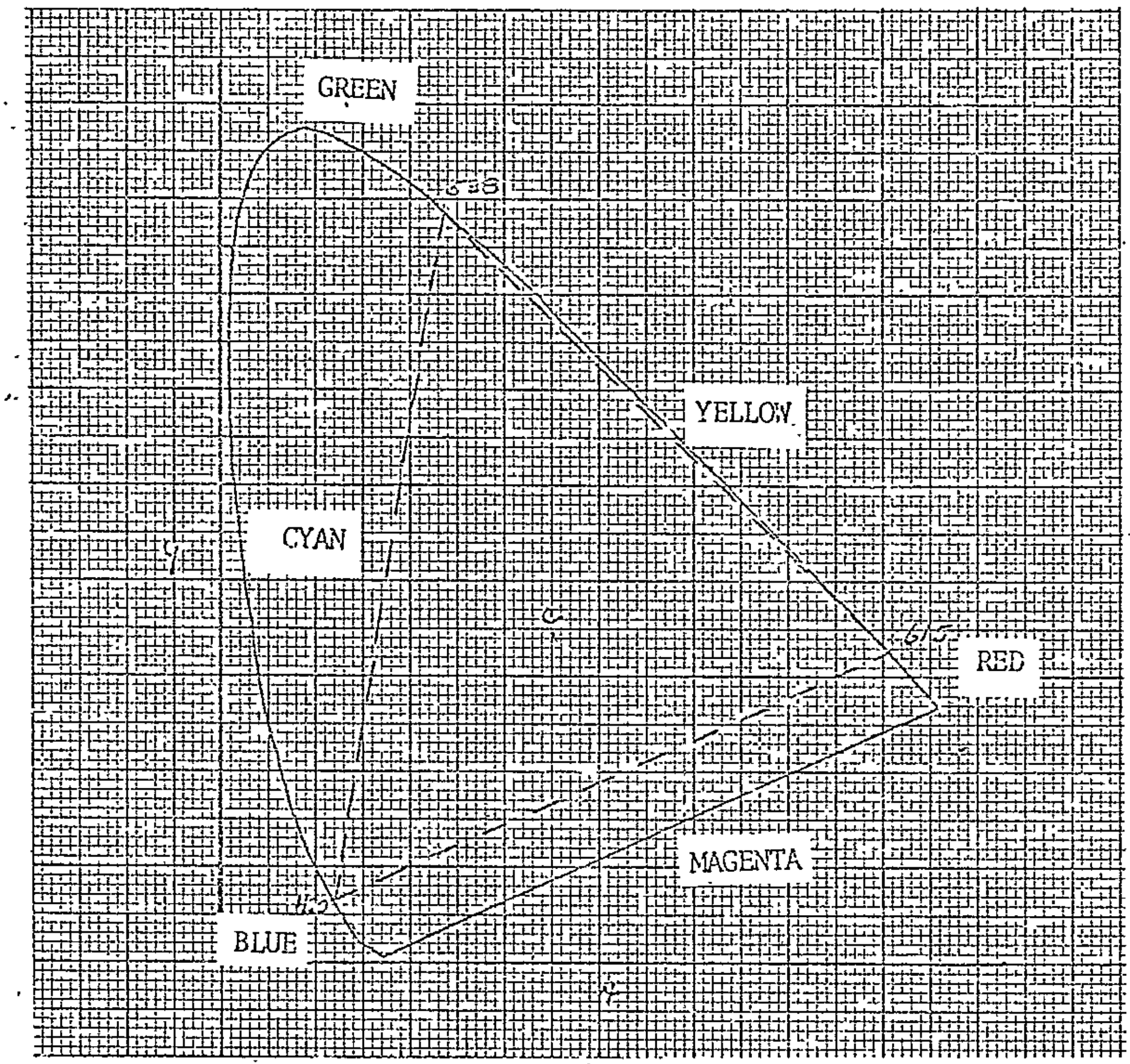


FIGURE -7

COLOR TRIANGLE: ALL COLORS WHICH LIE ON THE BORDER OR INSIDE THE TRIANGLE CAN BE REPRODUCED BY THE PRIMARIES AT ITS APICES. SATURATED CYAN (TO THE LEFT OF THE TRIANGLE) IS RARELY, IF EVER, ENCOUNTERED IN NATURE.

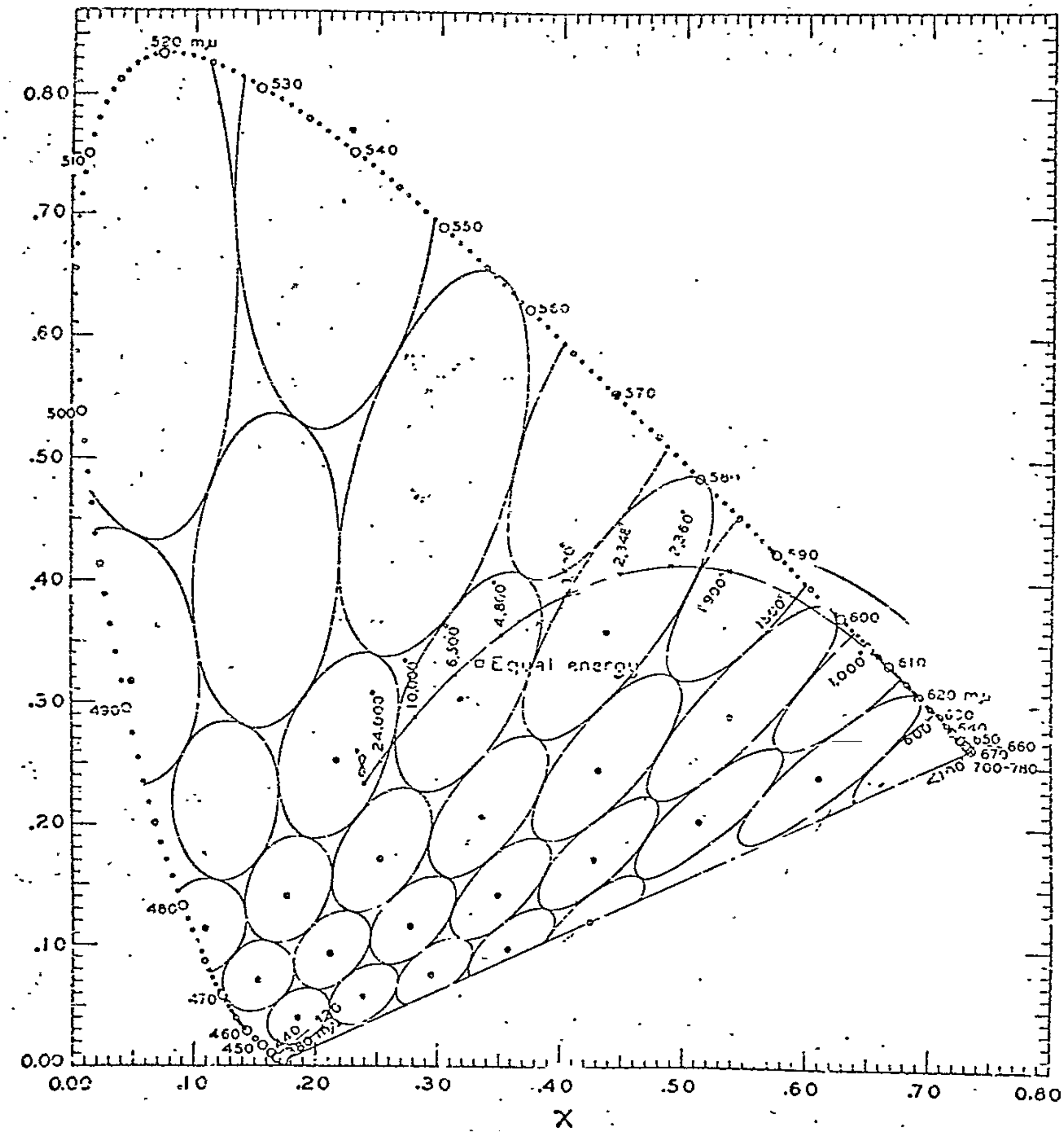


FIGURE 8

APPROXIMATE PERCEPTIBILITY OF CHROMATICITY DIFFERENCES ON THE CIE CHROMATICITY DIAGRAM.

The distances from points on the boundary of each ellipse to the indicated point within it all correspond approximately to one hundred times the chromaticity difference just perceptible with certainty under moderately good observing conditions.

energy distribution and may indeed be quite different spectrally. The advantage in using a trichromatic measurement of an image is that the resultant color measure is completely dependent upon the psyco-physics of the situation without any side effects of the human eye (e.g., simultaneous contrast enhancement) without regard to the phenomenon itself.

In the event multispectral photography is taken under cloudy or overcast conditions, the reflectance spectra of a ground object will not only be reduced in intensity but the curve will be altered in its shape. If there is no data available on the lighting conditions, the spectral reflectance variations with respect to some standard illuminant of a ground object will be attributed to properties of that object. Conversely, it is possible for an observer to falsely interpret some phenomenon in the ground scene because of what he feels to be a different illumination condition when in reality it may actually be an environmental variable which produced the observed image characteristic. Such distortions of colors and brightnesses of ground objects can be eliminated by the ability to simulate a standard illumination condition (such as noon sunlight) regardless of the actual intensity and spectral distribution of the scene illuminant as long as the relative intensity of the illuminant in each spectral band is known.

In order to control the appearance of a ground object on the multispectral photography, a multitude of colorimetric and spectroradiometric instruments have been employed to record not only the inherent

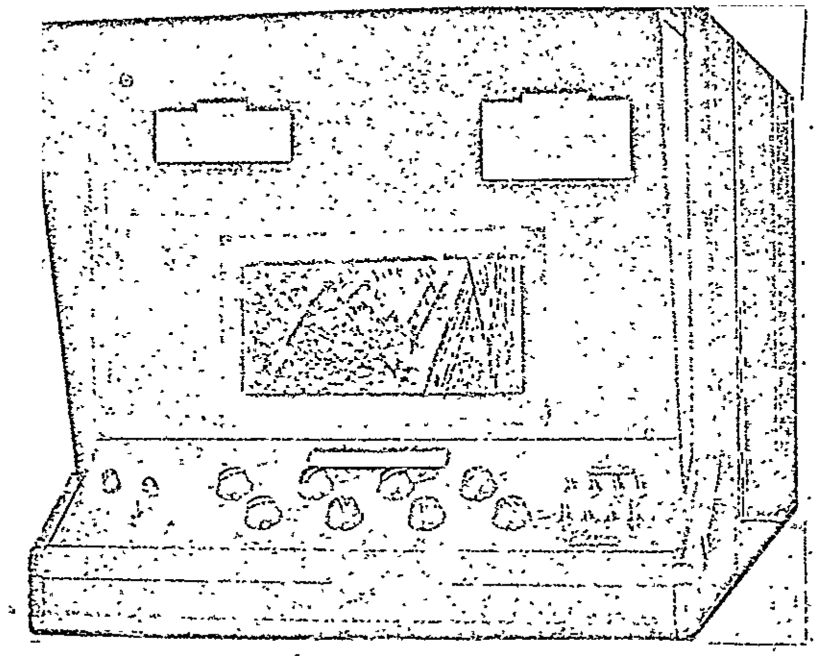


FIGURE 9: ADDITIVE COLOR VIEWER

Rear projection viewer superimposes four spectral photos taken by the camera creating a composite presentation in colo1

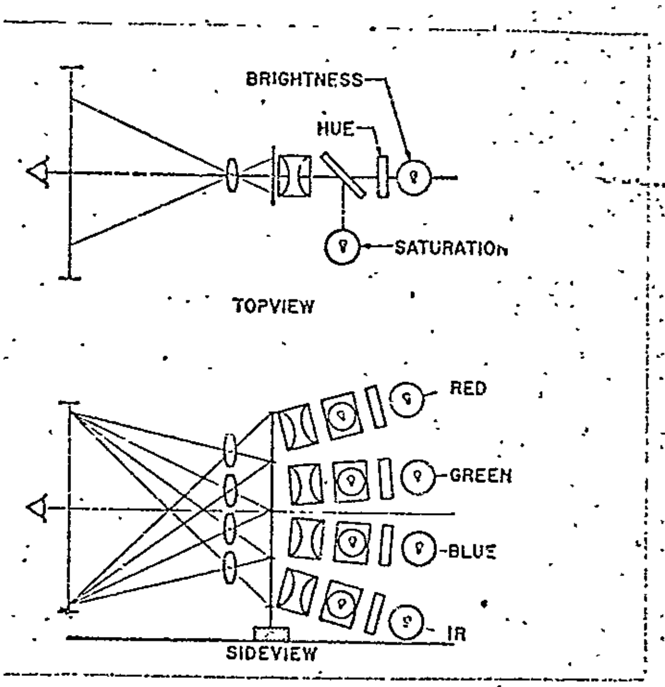


FIGURE 10: VIEWER OPTICAL SYSTEM

The optical projection system of the viewer gives in registered superimposition of all four spectral photographs on a rear projection screen. The illumination system allows the interpretor to control the brightness, hue and saturation of the image on the screen.

color of the object under the incident solar radiation encountered in the field but also its reflectance spectra. This permits an accurate comparison of the chromaticity of natural objects from the ground and from the additive color image presented on the viewer screen.

Often, the chromaticity of an object and its background lie reasonably close when plotted in the color solid. When this is the case, it is often judicious to employ a set of color projection filters which bear no resemblence to the taking filters but which have the effect of increasing the apparent chromatic difference between the ground object of interest and its background. This so-called false color mode can be made as distinct as the taking filters permit. The use of broad-band filters in the camera which overlap along the wavelength scale, may in some cases, make it impossible to chromatically separate the target image from background image. If however, the phenomenon of interest requires a set of narrow band taking filters, which area themselves non-overlapping, considerable color differences may be obtained.

2.3 Multispectral Viewer

The multispectral film viewer used in the experiment is shown in Figure 9. It is a desk type console which displays a rear projection screen to the operator. Optically, the viewer is an anolog of the taking camera. The four multispectral film images, each with its independent illumination system, are superimposed onto the viewer screen at a three times magnification and in precise registration, using the optical design shown in Figure 10. Misregistration of one image upon the other, when projected on the viewer screen, should not be greater than .1 millimeter so that no blur will be discernable at a standard viewing distance of 18 inches. The fixed magnification projection system utilizes four, five inch focal length, f/4.5 lenses. These lenses are critically matched so that their eqivalent back focus dimensions are within a few thousandths of an inch of each other. The differential distortion of the projection lens is matched in a unique way. As shown in Figure 10, a different part of the field angle of each viewer lens is used to project the image. This requires that the distortion of the lenses be different across their whole field but matched for all field angles associated with conjugate imagess.

Each of four images projected on to the viewing screen has its own dual illumination system which is also shown in Figure 10. This viewer utilizes 3200 degrees Kelvin lamps which have the advantage of being quite bright with the appropriate filament configuration to best fill the aperture of the projection lens. The brightness illumination passes through a neutral density filter, a spectral filter, a beam splitter and a condensing lens to illuminate the positive spectral photo. The greatest loss in energy throughout the system occurs through the spectral or color filter. The second half of the illumination system is set at 90 degrees to the brightness lamp and is employed for purposes of desaturation. Its illumination is reflected from the beam splitter and is added to the brightness illumination as modified by the color filter. The filters associated with the brightness illumination system controls the hue and brightness while the addition of a desaturation selection provides the photo-interpreter with complete contol over the displayed color.

Film flattening is provided by two optically polished glass plates, one of which is fixed to the viewer itself and is considered the focal plane or object plane of the viewer optical system. The other is mounted off the carriage through a spring loaded cam mechanism. This movable plate is raised off the fixed glass platen by means of a foot pedal during the transport of the film. This mechanism insures separation of the plates and avoids film scratching. A film guide is also provided to insure an even transport of the film in the horizontal plane, thus maintaining the registration which had been designed into the camera system.

Experience has indicated that the most satisfactory screen material for general rear projection viewing is a white Polacoat Lenscreen. Although other screens (such as the Kodak Dayview screen) provide a somewhat brighter image, the fall off with incident obliquity is more pronounced and the resolution capability is somewhat less. It was noticed however, that with the type Lenscreen used, considerable color infidelity existed when photographic reproductions of the multispectral viewing screen were attempted. A recently developed type of plexiglass Lenscreen which is designed specifically for exposing accurate color photographs of rear projected scenes has been used for photographic reproduction of the screen image.

In summary, the multispectral viewer projects four multiband images contained on a single piece of film (each one of which has a resolution of 45 lines pairs per millimeter) at a magnification of 3 X, resulting in a screen resolution of about 15 lines per millimeter. Since the average eye resolves seven lines per millimeter at a normal 18 inch viewing distance, a permissable misregistration which does not exceed .0056 inches has been specified and designed into the camera-viewer system. Each projection lens has its own brightness lamp and filter set which illuminates one of the spectral records as well as a desaturation lamp. By placing various combinations of projection filters into the optical path and by linear transportation of a filter rack, the scene on the viewing screen appears in color. An important feature of the system is that it frequently enables, through proper choice of camera and viewing filtration, the detection, recognition and identification of objects by color differences which would not otherwise be visible.

SECTION 3

THE EFFECTS OF PHOTO PROCESSING ON IMAGE COLOR CHARACTERISTICS

The chromatic characteristics of the multispectral image which is formed by additive color methods on the viewer screen are significantly affected by the photo processing techniques used. The relationship of exposure (or its radiometric equivalent) to density on both the negative film used in the camera and the positive transparency printed for projection in the viewer is a critical consideration. Also a significant parameter, often overlooked, is the maximum and minimum density of the duplicated positive image.

Herein the fundamental relationships of the additive color image are examined in some detail in order to present to the reader the significance of photo processing and how errors associated with processing may be reduced or eliminated. Specific examples, experimentally obtained, are included to demonstrate salient points.

3.1 Characteristics of the Multiband Negative

When a multiband negative is properly exposed and processed to a gamma of 1.0, a one to one correspondence will be created on the linear portion of the characteristic curve between the radiation reflected by ground objects and the corresponding density of the images on the film. Frequently however, as will be demonstrated in the latter part of this section, a gamma considerably greater than unity is necessary to chomatically differentiate objects whose spectral signatures may be nearly similar.

An ideal set of multiband negatives will reproduce a grey scale target having unifrom spectral reflectance and which is illuminated by a uniformly distributed source of radiation in such a way that the image density of each grey scale is the same on every one of the individual multiband negatives. This exact matching of exposure and gamma in the different spectral bands which are used is very difficult and frequently not possible.

The difficulty in exactly matching the exposure density relationship (the characteristic curve) is due almost entirely to the effect of the wavelength of radiation which strikes the photographic emulsion. When one roll of film is used to expose all four spectral bands of distinctly different wavelengths, in general, the characteristic curve associated with each band will be different. This condition is unfortunately encountered in panchromatic emulsions. This effect is shown in Figure 11, in which the characteristic curves for Infrared Aerographic film (5424) exposed with the filters used in the experiment.

The so-called Aerial Exposure Index (or speed) of photographic emulsions used in multiband photography also varies depending on both the spectral sensitivity and the filtration used. The Aerial Exposure Index is defined as .5 divided by the exposure (meter candle seconds) at the point where the shape of the characteristic curve is .6 times the gamma, (the tangent of the angle made by the linear part of the curve

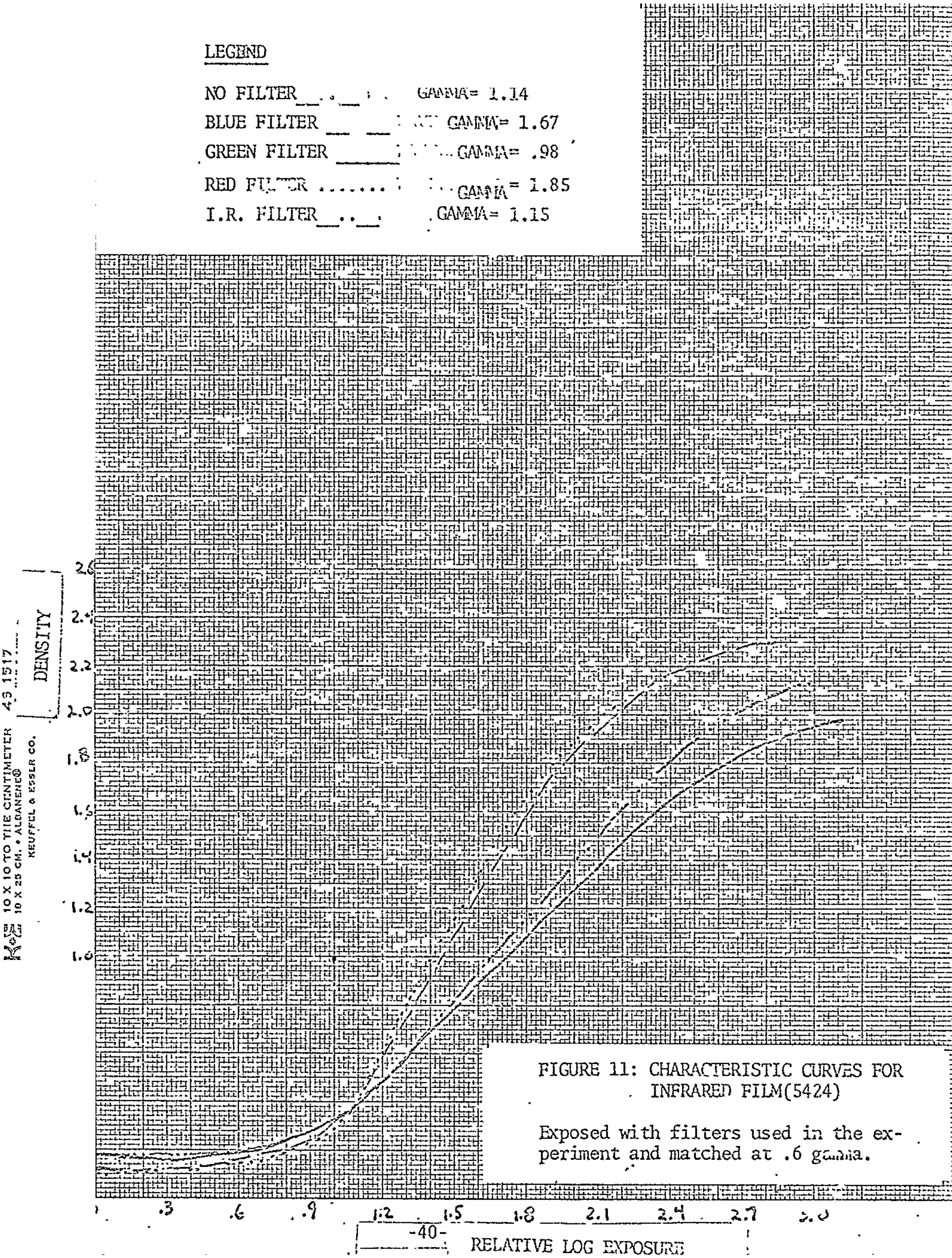


FIGURE 11: CHARACTERISTIC CURVES FOR INFRARED FILM(5424)

Exposed with filters used in the experiment and matched at .6 gamma.

and x axis). Figure 12 shows the absolute relationship of the characteristic curves and the differences in photographic speed for Aerographic infrared film (5424) using filters similar to those used in the experiment.

The careful reader will note that exposure is measured in photometric units of meter candle seconds and hence is defined only for the visible spectrum. The exposure of the infrared band contains no visible light and is really not capable of definition in terms of photometric exposure. It has been the practice in infrared (and ultraviolet) aerial photography to use the fiction that the exposure in this non-visible region consists of the meter candle seconds of a standard energy source (Luminant C) which has a predefined spectral distribution of both visible and infrared radiation. This practice has the effect of making exposure calculations for the infrared bands extremely difficult to determine in practice because of deviation of the spectral distribution of solar radiation from this standard. Accurate and unambiguous exposure can be obtained in multiband photography by using absolute radiometric units (watts per centimeter squared) in each spectral band. This was the technique used in this experiment and resulted in very accurate calculations of exposure as will be seen from the experimental results to be presented in Section 5.

It should be noted that the intensity of the energy which forms the image on the photographic emulsion of an airborne multispectral camera

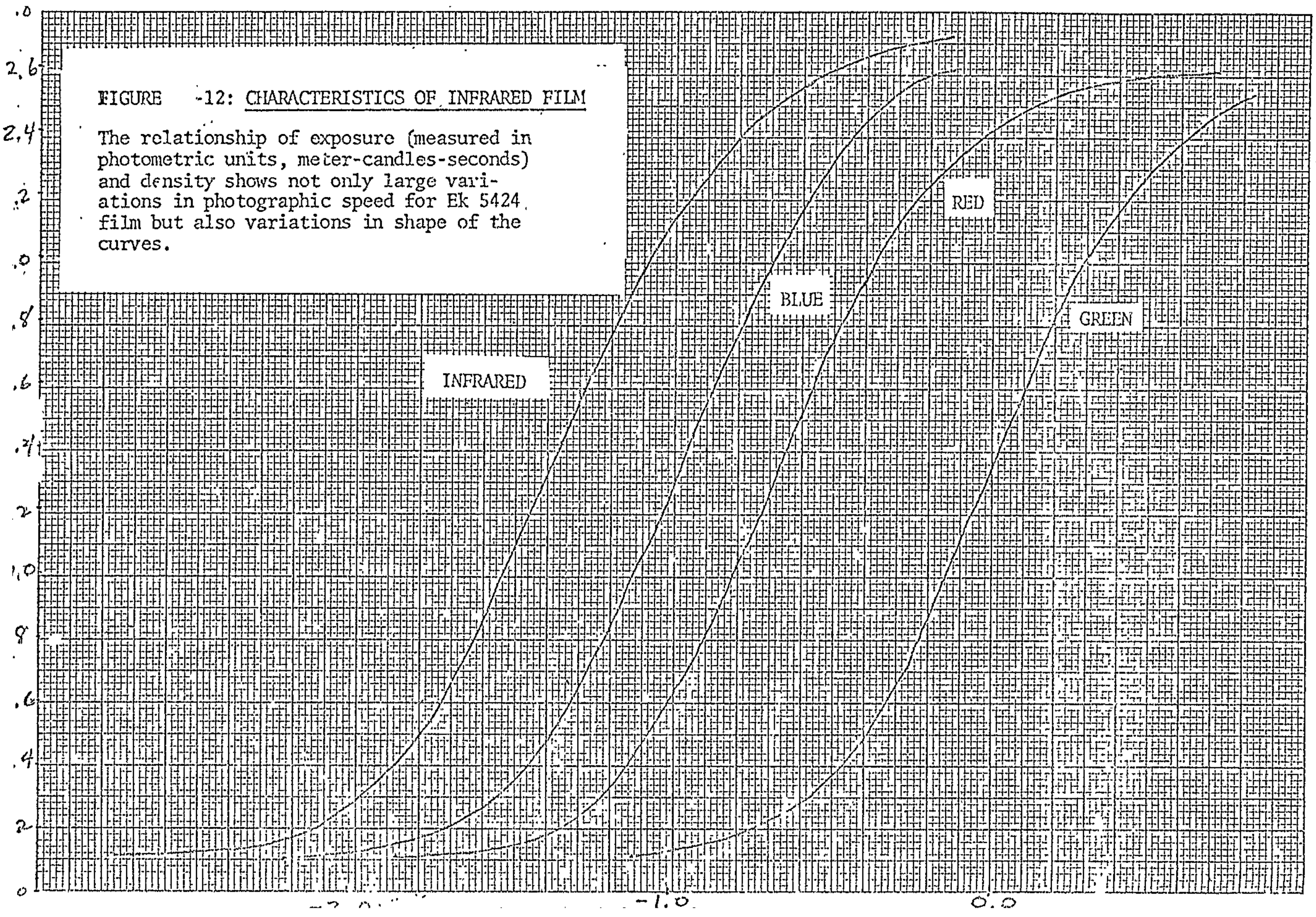


FIGURE -12: CHARACTERISTICS OF INFRARED FILM

The relationship of exposure (measured in photometric units, meter-candles-seconds) and density shows not only large variations in photographic speed for Ek 5424 film but also variations in shape of the curves.

does not depend on the distance between the object and the lens of the sensor. That is, when an object is a sufficiently large distance with respect to the focal length of the camera, the intensity of the radiation which forms the image is:

$$I = \frac{B \pi}{4 f^2}$$

Where: B = incident intensity of radiation times the reflectivity of the object.

f = f/number of the lens

In obtaining actual multispectral photographs, the experimentor must also include the actual lens and filter transmission characteristics in the above equation.

3.2 Tone Reproduction

In order to accurately reppesent to the human eye the reflected light from a particular ground scene, there must exist (in the language of mathematics) a one to one mapping from the object luminance space into the positive density space. Assume that the negative has been well exposed and processed to a particular gamma. A tone reproduction curve may be constructed to represent the fidelity with which combination negative and positive transparency reproduces the brightness of the original ground scene. A typical tone reproduction curve is shown in Figure 13, which represents the fidelity with which the red spectral band re-

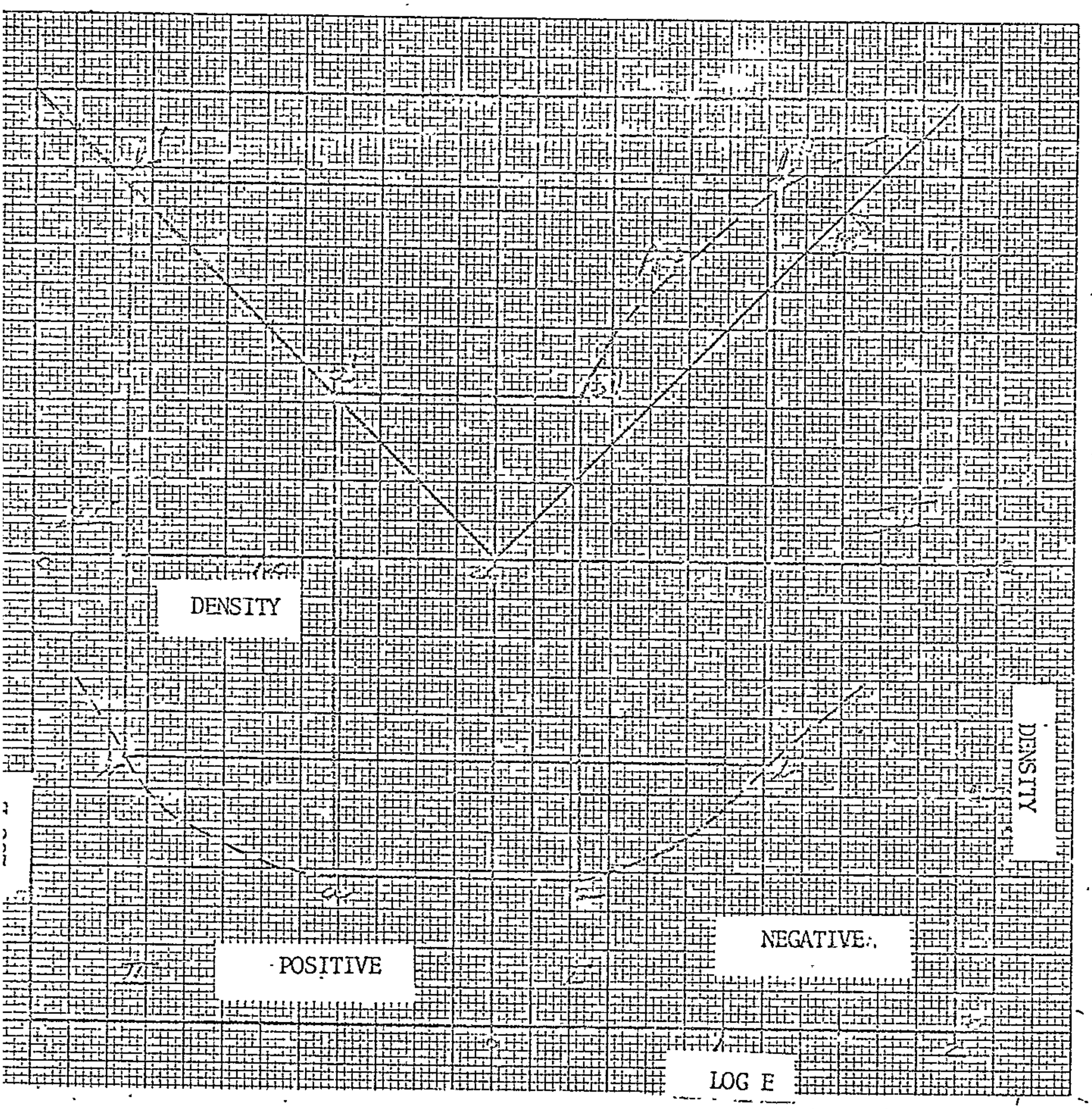


FIGURE -13: TONE REPRODUCTION DIAGRAM

This diagram shows how well the red spectral negative and duplicated positive reproduced the original scene brightness.

produced the five step grey scale under noon illumination at Davis, California on 31, July 1967. Quadrant I of this figure shows the characteristic curve of the spectral negative. The densities on the negative of the displayed grey scales in the scene were measured and the target brightness in relative units related to the photographic exposure on the negative film. The corresponding characteristic curve of the positive transparency was obtained through similar measurement of the grey scale densities of quadrant II. Vertical lines from several points connecting the negative and positive characteristic curves are made to intersect a 45 degree transfer line in quadrant III. By extending horizontal lines from quadrant III to intersect vertical lines from the original negative curve of quadrant I, and indication of reproduction process is obtained. Thus, the locus of all intersected points from the negative and positive characterisitic curves yield the tone reproduction of quadrant IV. For exact reproduction, the curve in quadrant IV should appear as a straight line. An indication of the reproduced departures from this norm are made by comparing the curve A with the curve B.

3.3 How Image Density is Related to Color

In order to create an additive color presentation from a set of black and white multiband photos, each photograph must be projected by an optical system, each using a different colored light source, onto a screen in such a way that the images are accurately registered with respect to each other. A different proportion of light will be present in the screen image depending upon the densities of the image on each multiband photo which is projected.

In establishing the relationship between density of individual black and white images and the color characteristics of the correspon-ding recombined image that is projected on the screen, consider the three primary taking filters, blue, green and red, that were used in this experiment. Each multiband negative was exposed through one of these filters, processed to obtain a specific characteristic curve (gamma); a positive image was made by exposing the negative onto dup-licating film and processing this film to obtain a specific relationship between the brightness of the ground scene and the density of the image on this positive transparency.

By projecting each of these multiband positives using similar blue, green and red filters to form the aidditive color presentation on a view-ing screen, a so called "true color" rendition of the ground scene is created. The fidelity of the colors of the image compared to the ob-ject is not perfect. In order for the image to be a perfect reproduction of the color of the object it would be necessary to photograph the images exactly as would be recorded by the stimulation of the visual response mechanism of the human eye, shown in Figure 14. To date it has not been possible to construct with complete fidelity filters whose transmission could be supplemented by the response of a photo sensitive material and

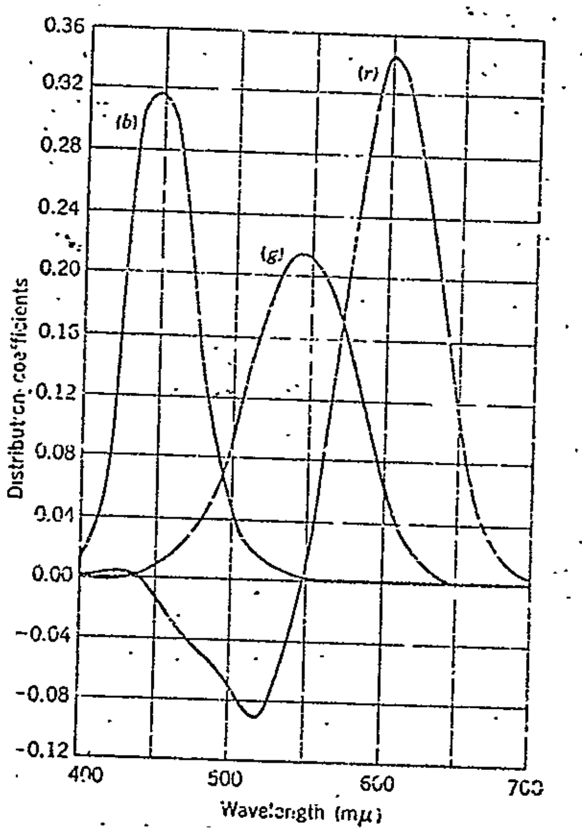


FIGURE -14

SPECTRAL DISTRIBUTION CURVES FOR THE CIE "STANDARD OBSERVER" AND MONOCHROMATIC PRIMAIRES AT THE WAVELENGTHS 700 mμ, 546.1 mμ, and 435.8 mμ.

the illuminant falling on the scene such that these curves are exactly reproduced. Due to the necessity to create a less than zero exposure, it is usually assumed that it is theoretically impossible to obtain absolutely perfect color reproduction without using the human eye. These facts not withstanding, a very close true color reproduction of a ground scene is possible with the blue, green and red filters used in the experiment.

As discussed in Section 2, not all colors can be reproduced using one particular set of filters due to the shape of the color triangle created within the chromaticity diagram (see Figure 7). No difficulty will be encountered in reproducing colors whose dominant wavelengths lie close to the transmission peaks of the taking filters. However, in order to reproduce the colors of objects which reflect only dominant wavelengths associated with secondary colors yellow, cyan, it is necessary that there exist a wavelength overlap between the taking primaries as shown in Figure 15. That is, the overlap region between the red and the green filter will yield the yellows and in similar manner the overlap region between the blue and green filter will yield cyan color. The number of millimicrons of overlap indicate the spectral region in which the secondary colors can be reproduced. Fortunately, for true color reproduction, most colors in nature are composed of broadband which cover a considerable wavelength range.

The reproduction of the secondary colors is also dependent on the

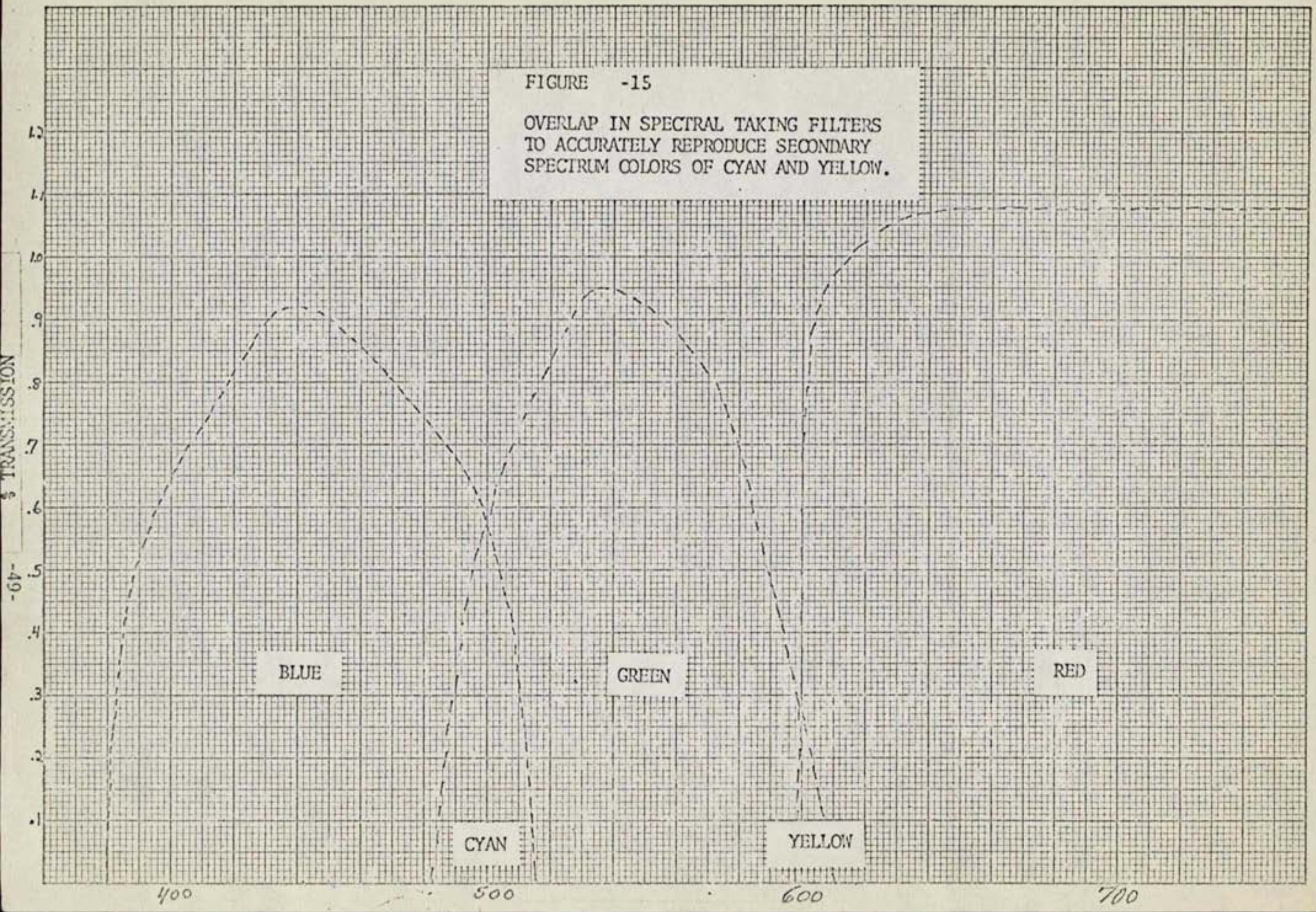


FIGURE -15

OVERLAP IN SPECTRAL TAKING FILTERS TO ACCURATELY REPRODUCE SECONDARY SPECTRUM COLORS OF CYAN AND YELLOW.

camera exposure. Since the region of overlap does not possess the amplitude of transmission which the primary colors do, too short an exposure will render only the primaries visible. As the exposure time is increased the secondary colors will become apparent.

In view of the foregoing discussion, the image density on each of the multiband positives can now be related to the additive color image which they produce:

1 - Where the densities on all the multiband positives are equal, a condition of zero saturation exists; the image is a shade of grey (achromatic). This is due to the fact that the human eye sees equal amounts of blue, green and red which are combined in the image as being white. The brightness of luminosity of the white color which is perceived depends on the total energy combined in the image.

2 - The color of the image is a function of the ratio of the three colors which are projected to form it. Since the densities on each multiband photo are a logarithmic relation of the image forming energy, the chromaticity is obtained as the weighted average of the three densities.

3 - The additive color image will faithfully reproduce the color of an object at a gamma of one. Increase

in gamma above unity will increase the saturation of the image color above that of the object. Conversely, a gamma less than unity will decrease the saturation of the additive color image.

4 - The magnitude of the minimum density multispectral image establishes the brightness of the additive color image.

3.4 Experimental Results

The theoretical considerations discussed above were empirically evaluated during the course of the experiment. A four color target was placed on the ground along with a five step grey scale. Multiband imagery was obtained at 1000 feet altitude at Davis, California at 1130 PDT, 31 July 1967.

Since a calibrated grey scale was used along with the color panels, it is possible to relate the density characterisitics of the image directly to the brightness of the ground scene by comparing the image density on the positive with the reflection density of the grey scale. In this way the fourth quadrant of the tone reproduction diagram was produced directly without the necessity of using the individual negative and positive characteristic curves shown in quadrants I and II (Figure 13).

Four reproductions of the viewer screen additive color image are shown in Figure 16. Each rendition has been created by the addition of the blue, green and red spectral bands to form a "true color" reproduction of both the color targets and grey scale on the ground. Each of the sets of spectral positives was processed and projected so that the grey sclae target remained acromatic (without color). The characteristic curves of the multispectral photography associated with these photographs (and hence the gamma) are shown in Figure 17. Note that longitudinal displacement of the green spectral characteristic curve away from the red and blue is compensated by the adjustment of the brightness when the image is projected in the additive color viewer. Non-linearity of the characteristic curve of the red spectral band (graphs A and B of Figure 17) presents a more serious problem. In cases where the slppe of the characteristic curve (gamma) of the blue, green and red spectral positives differ, the color of an object will vary with exposure. For instance, a grey scale such as that shown in Figure 16 might typically be bluish at the dark end, grey in the center and reddish at the bright end.

Color measurement of the chromaticity of the four color images and the lightest grey scale is shown in Figure 18. Note how the color becomes more saturated (moves away from the center of the chromaticity diagram) as the gamma is increased. In all cases the image of the lightest grey scale has been placed at the chromaticity coordinate (WH) in the diagram by manipulation of the viewer controls. In theory,

FIGURE 16-A

FIGURE 16-B

FIGURE 16-C

FIGURE 16-D

MULTISPECTRAL TRUE COLOR REPRODUCTION OF TARGET PANELS AND GREY SCALES PHOTOGRAPHED AT 1000 FT. ALTITUDE. GAMMA INCREASES FROM TOP TO BOTTOM RESULTING IN INCREASED SATURATION OF ALL COLORS. NOTE THAT IN ALL FOUR PHOTOS THAT THE GREY SCALE REMAINS "COLORLESS" AS COLOR PANELS BECOME MORE SATURATED.

FIGURE 16

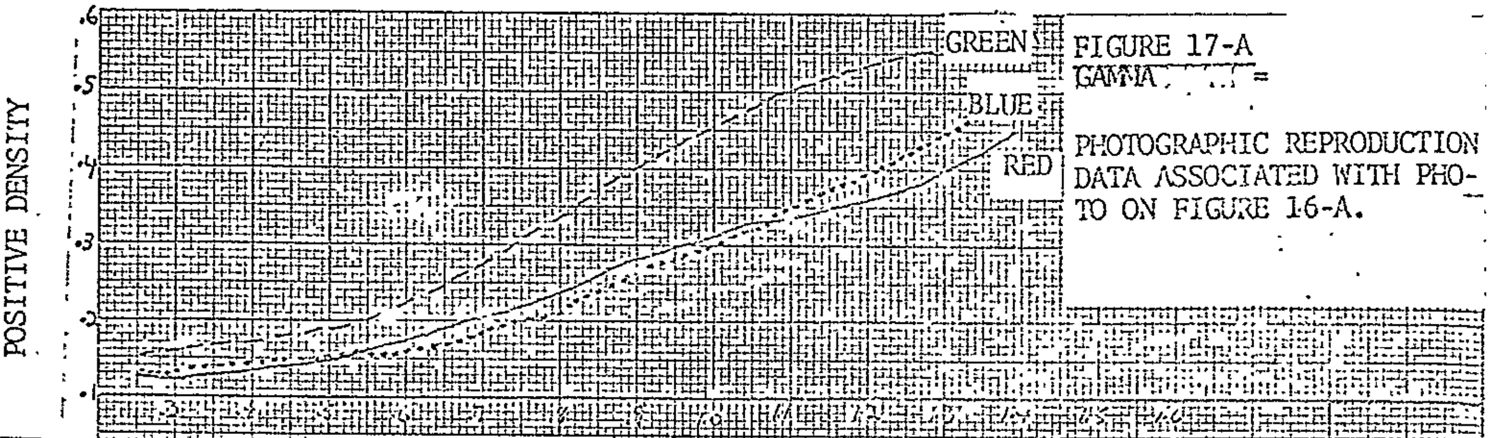


FIGURE 17-A
GAMMA =

PHOTOGRAPHIC REPRODUCTION DATA ASSOCIATED WITH PHOTO ON FIGURE 16-A.

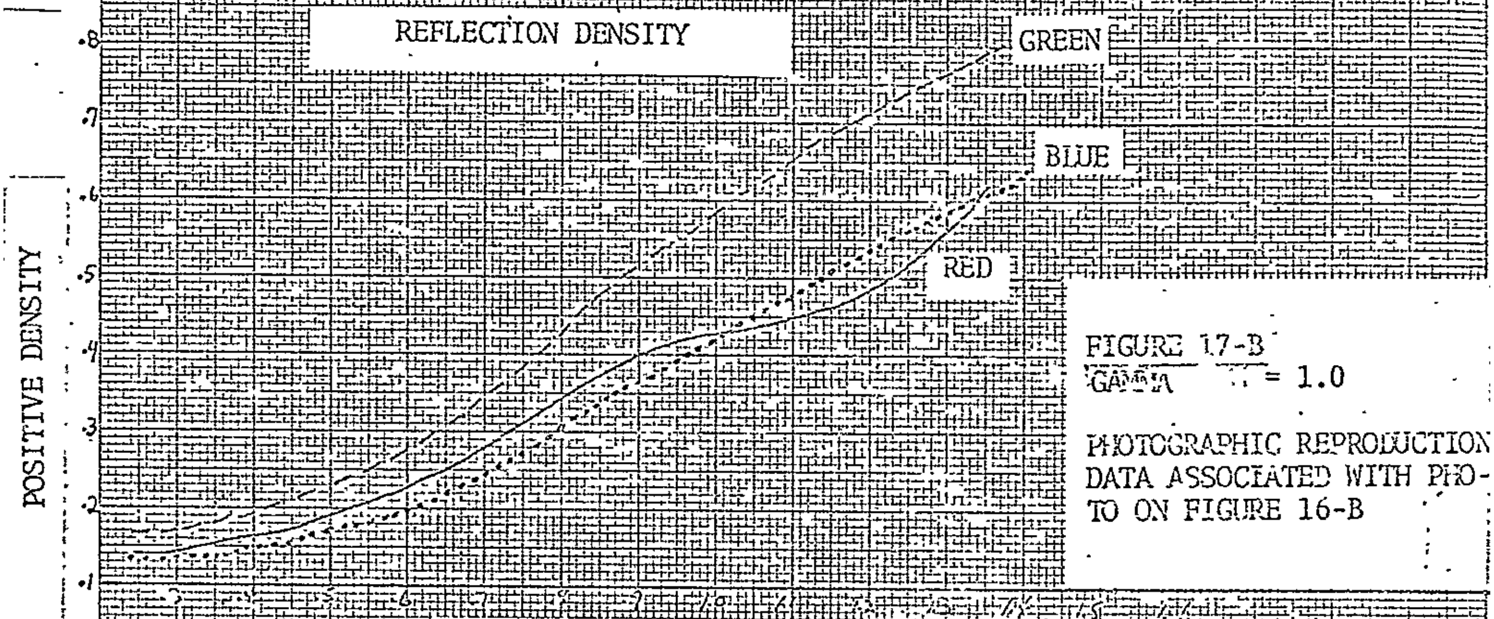


FIGURE 17-B
GAMMA = 1.0

PHOTOGRAPHIC REPRODUCTION DATA ASSOCIATED WITH PHOTO ON FIGURE 16-B

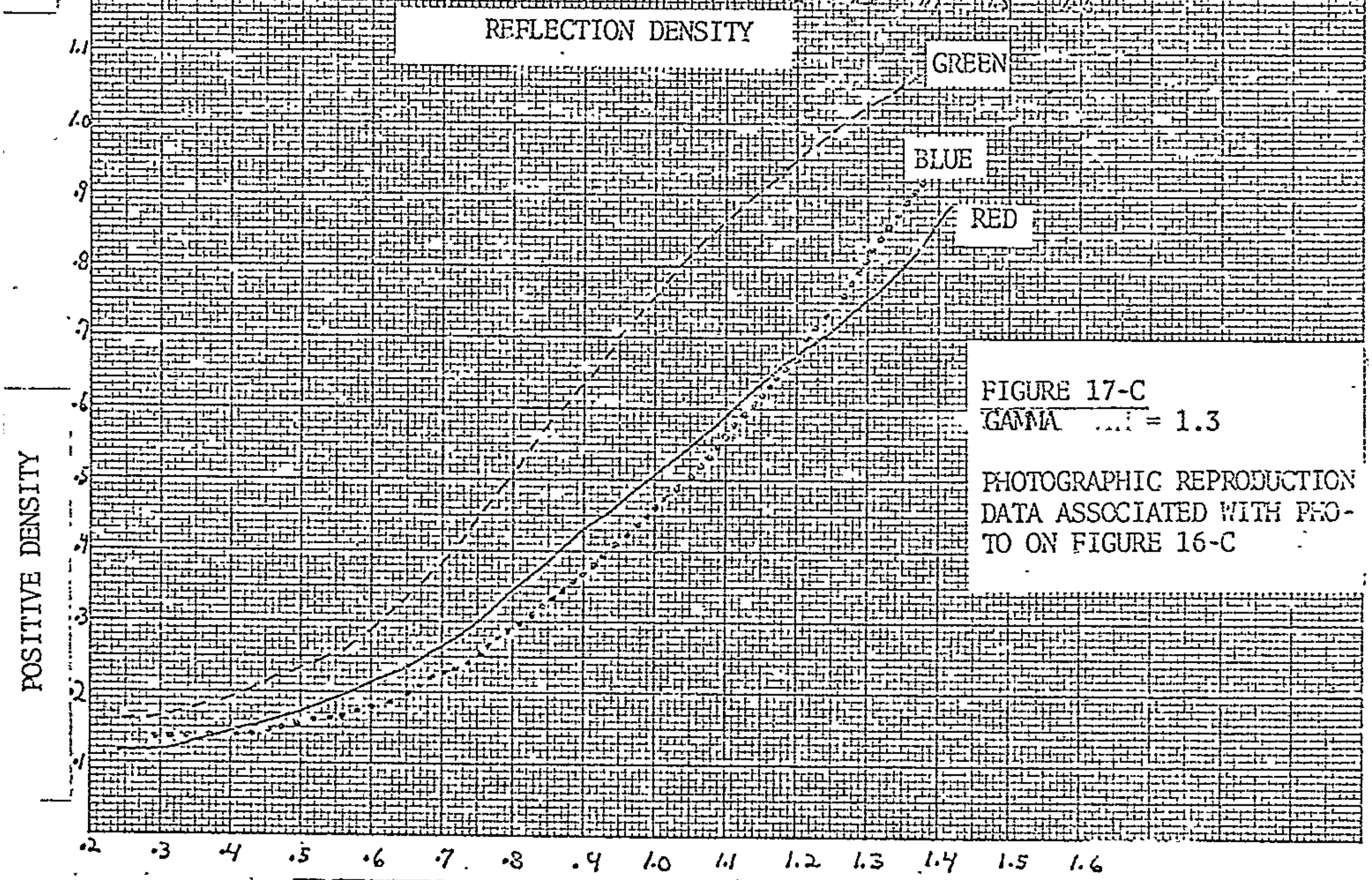


FIGURE 17-C
GAMMA = 1.3

PHOTOGRAPHIC REPRODUCTION DATA ASSOCIATED WITH PHOTO ON FIGURE 16-C

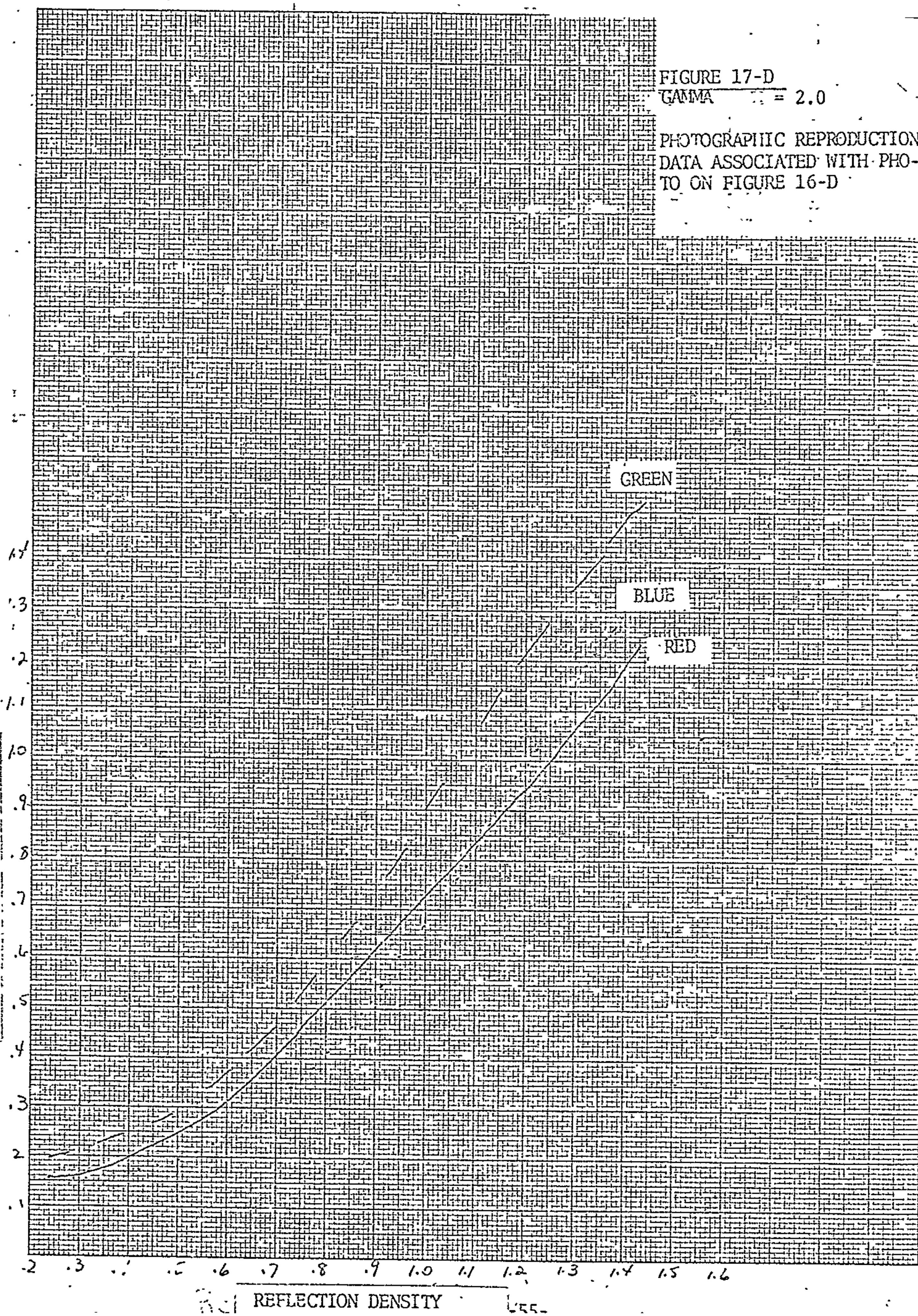


FIGURE 17-D
GAMMA = 2.0

PHOTOGRAPHIC REPRODUCTION DATA ASSOCIATED WITH PHOTO ON FIGURE 16-D

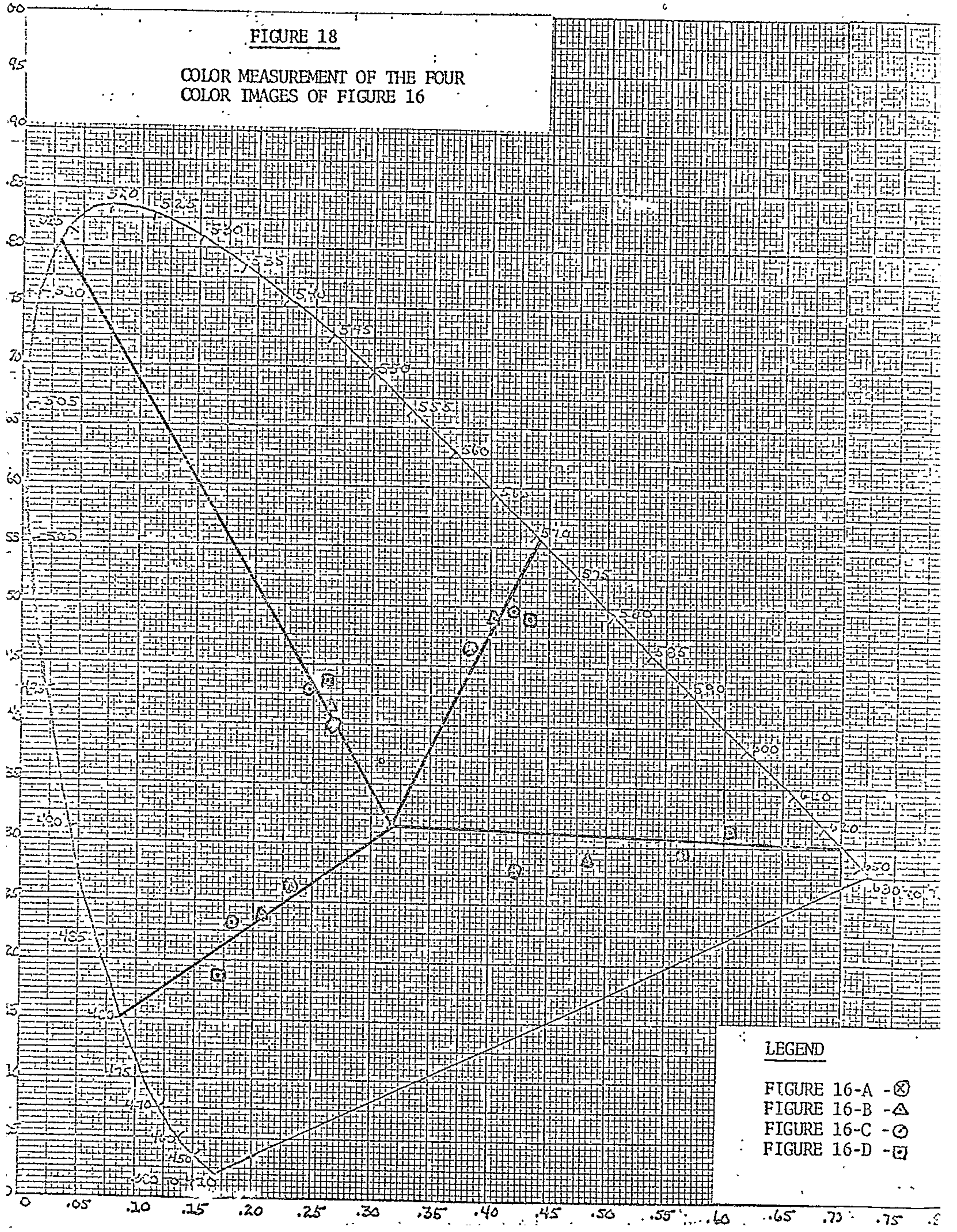


FIGURE 18

COLOR MEASUREMENT OF THE FOUR COLOR IMAGES OF FIGURE 16 all the points should lie on a line from the center of the diagram. The deviations from a constant dominant wavelength is probably caused by variations in processing, particularly in the red band, as previously noted.

An often overlooked aspect of color reproduction is the effect of the maximum and minimum density on the color of the image produced. The effect of reduced brightness as the maximum density is increased while the gamma is kept constant is shown in Figure 19. Relatively dark objects such as the green target panel and grass areas lose color first while brighter objects such as the yellow target and soil still remain relatively bright to the eye.

FIGURE 19-A

FIGURE 19-B

FIGURE 19-C

VARIATIONS IN BRIGHTNESS OF TARGET PANEL DUE TO VARIATIONS IN THE DIFFERENCE BETWEEN MAXIMUM AND MINIMUM DENSITY.

FIGURE 19

SECTION 4

INCIDENT SOLAR RADIATION, THE SPECTRAL REFLECTANCE AND COLOR OF GROUND OBJECTS.

The quantitative analysis of the chromatic characteristics of multiband and conventional color photography is greatly facilitated by measurement of the color and spectral characteristics of "standard" targets embedded in the environment. In order that temporal errors may be eliminated, it is essential that these measurements be made at the time the photography is taken. This data has three important purposes.

(1) It allows an independent check to be made on exposure calculations and film processing characteristics.

(2) It permits compensation of the effects of incident solar radiation and the spectral attenuation of the atmosphere on the characteristics of the color image.

(3) The chromatic characteristics of images of other "natural" objects in the environment (e.g., soils, vegetation, etc.) can be related to a standard system of color measurement.

At each test site the standard target consisted of an array of four color panels: blue, green, yellow and red and a five step grey scale which had nominal reflectance values of 4, 8, 16, 32 and 64 percent.

The intensity and spectral distribution of incident solar radiation was obtained each time the reflectance spectra and color of the panels were measured. In this way it was possible to measure the effect of variations in the incident radiation on both the spectral reflectance characteristics and color of the panels.

Spectroradiometric measurement of incident solar energy was obtained using a battery operated spectroradiometer covering a range of 380 to 1250 nanometers (See appendix A). The instrument incorporated a Lambertian detector surface which resulted in measurement of the total energy (sun plus skylight) falling on the earth's surface. The sensitivity of the device ranged from 0.01 to 1000 microwatts per centimeter squared per nanometer with a half power bandpass of 15 nanometers in the visible range and a 30 nanometer bandpass in the infrared portion of the spectrum. The relative accuracy of the data obtained (not the absolute accuracy) was plus or minus 3 percent.

Reflectance measurements were made using two narrow angle (12 degree total field) spectroradiometers, one covering 350 to 750 nanometers and the other 750 to 1350 nanometers (See Appendix A). The bandpass of the instruments was 5 nanometers in the visible spectrum and 10 nanometers in the infrared. The relative point to point accuracy of the reflectance spectral data obtained with these instruments was

FIGURE 20:

REFLECTANCE SPECTRORADIOMETER

SPECTRORADIOMETERS BEING USED TO MEASURE INCIDENT SUNLIGHT

plus or minus 2 1/2 percent.

Colorimetric measurements were taken using a photo-electric colorimeter which read the tristimulus values (X, Y, Z) of the object as illuminated by natural sunlight. The specific details of this instrument and the three spectroradiometers discussed above are presented in detail in Appendix A which includes information on the calibration of the instruments.

4.1 Incident Solar Radiation

The intensity and spectral distribution of solar radiation falling upon the earth's surface is known to vary with solar angle and atmospheric conditions. Knowledge of the characteristics of solar energy which actually strikes the ground is important since an object will reflect different amounts of this radiation in each spectral band sensed by the camera in direct proportion to that which falls upon the object.

Theoretical analysis of solar illumination based upon air mass calculations and Raleigh scattering of the aerosols are of little practical value in predicting the spectral distribution of solar energy which actually reaches the ground. This is primarily due to the existance of unknown amounts of Mie scattering and absorption in the atmosphere due to particles which are large compared to the wavelength of the radiation.

Figure 22 demonstrates this condition. Spectroradiometric readings

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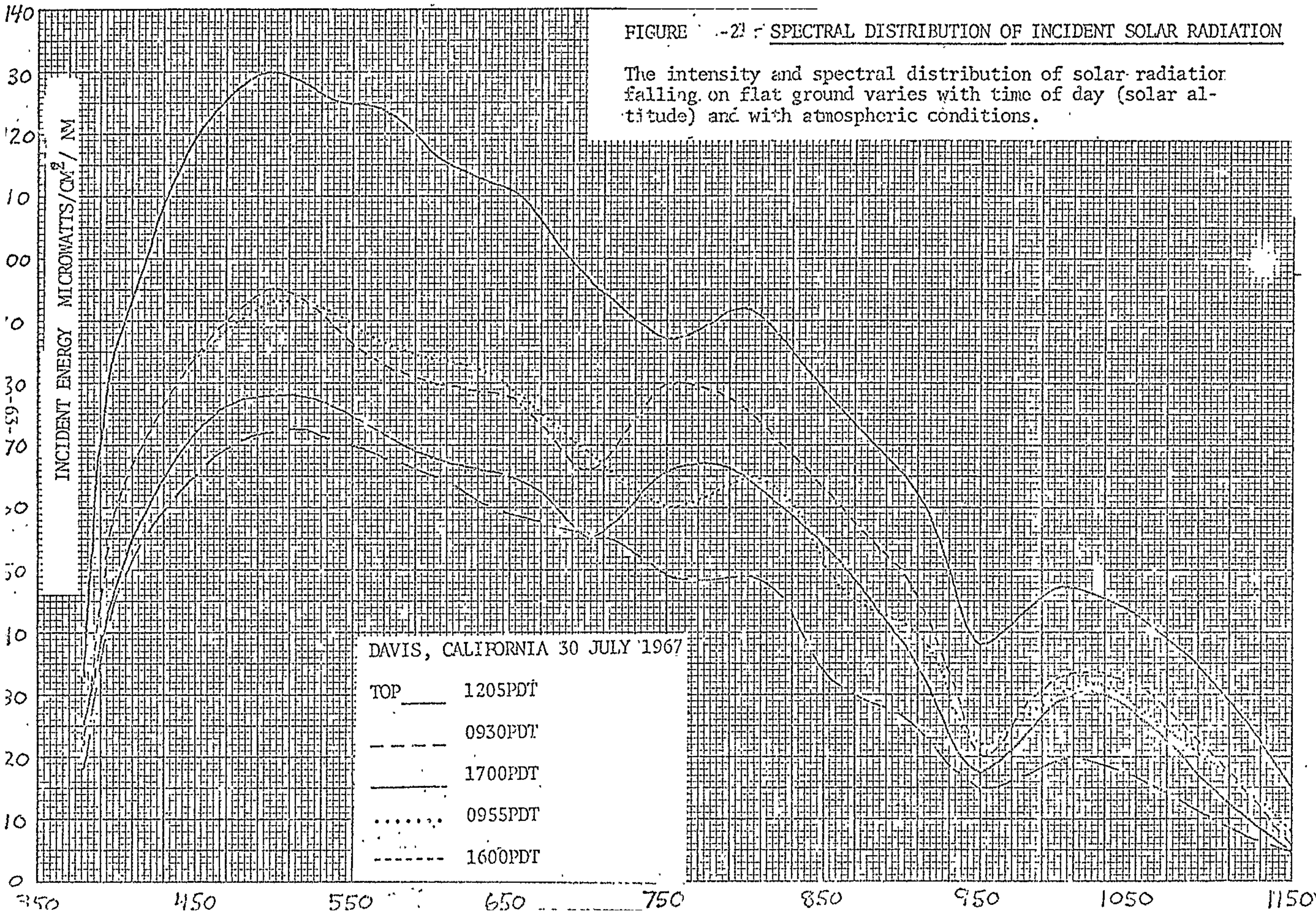


FIGURE [illegible]-2 SPECTRAL DISTRIBUTION OF INCIDENT SOLAR RADIATION

The intensity and spectral distribution of solar radiation falling on flat ground varies with time of day (solar altitude) and with atmospheric conditions.

of solar energy (both sunlight and diffuse skylight) using a lambertian detector were measured on 30 July 1967 at Davis, California. Spectral intensity in microwatts per centimeter squared per nanometer from 380 to 1150 nanometers was measured at five times during the day.

The first feature clearly evident from this data is the large variation in intensity with wavelength as a function of time (solar angle). The characteristic absorption band below 380 nanometers and at 950 nanometers is also clearly evident for all the times recorded. Of particular significance, however, is the presence of considerably more infrared radiation in the 700 to 900 nanometer band in the afternoon compared to the morning. The reader will notice that although the visible radiation, 400 to 700 nanometers, has an average increase in radiation of 8 percent (with a maximum of 13 percent) in the afternoon, the infrared radiation in the 700 to 900 band exhibits an average increase of 25 percent and is occasionally as high as 40 percent in the afternoon compared to the morning. The reduction in visible light in the afternoon is conventionally attributed to the absorption of smoke and dust particles in the atmosphere.

The effects of variation in the solar radiation in the solar radiation striking the terrain, if known, can be compensated in multispectral photography since the exposure in each spectral band can be independently adjusted. Color infrared film on the other had has fixed spectral sensitivity of the individual dye layers and consequently the images of ground objects taken under these conditions appear more red in the afternoon than in the morning.

There is one aspect of solar illumination that can not be compensated by variation in exposure in the multispectral camera. This is the spectral difference between the solar radiation illuminating the ground and the diffuse skylight which illuminates shadowed areas. Figure 23 shows a comparison of direct sunlight and diffuse skylight made at the same time on 30 July 1967 at Davis, California. In addition to the obvious reduction in intensity, skylight is predominantly blue which results in an apparent increase in the blue band exposure when an object is in the shade of topographic features. The reader must be cautioned that the spectral distribution of the shadows cast by trees may be quite different from that shown in the preceeding figure due to transmission and secondary reflection of the leaves.

4.2 Spectral Reflectance of Ground Objects

Remote sensing instrumentation in the .26 to 3 micron band of the electromagnetic spectrum practically without exception utilizes solar radiation as the energy source. As was seen in the preceeding paragraphs, this energy varies continuously during the day due to sun angle and atmospheric conditions. The spectral distribution of solar energy which is reflected by a ground object will also vary as a function of both the orientation of the object and its absorption-transmission-reflection characteristics.

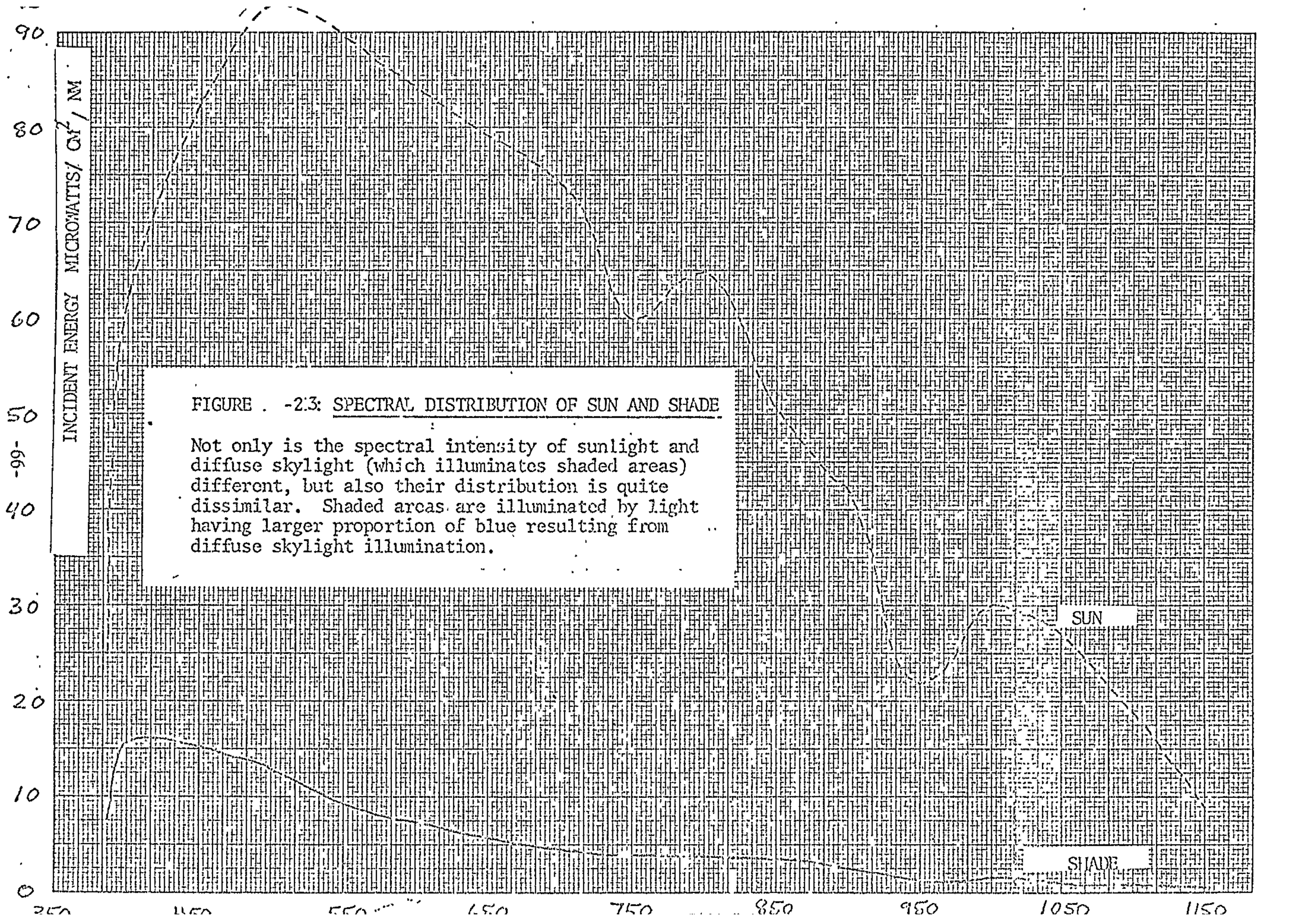


FIGURE . -2.3: SPECTRAL DISTRIBUTION OF SUN AND SHADE

Not only is the spectral intensity of sunlight and diffuse skylight (which illuminates shaded areas) different, but also their distribution is quite dissimilar. Shaded areas are illuminated by light having larger proportion of blue resulting from diffuse skylight illumination.

Figure 24 demonstrates the significant differences which exist between laboratory spectrophotometric measurements of the reflectance spectra of color target panels and field measurements which utilize solar radiation as the illuminant. In order to facilitate comparison, the field spectral data have been normalized to noon sunlight conditions that existed on 30 July 1967 and then equated to the laboratory data at 555 nanometers. The blue and green panels are seen to exhibit considerably reduced reflectance under natural sunlight compared with laboratory measurements. The red panel on the other hand, showed approximately a 22 percent reduction in reflectance at 725 nanometers but an 18 percent increase at 800 nanometers. It must be emphasized that the reflectance characteristics of objects under natural solar radiation are continually changing as a function of the intensity and distribution of the illuminant. For this reason, the density of the image which appears on a spectral photograph can not be predicted on the basis of laboratory spectrophotometric data showing percent total diffuse reflectance as a function of wavelength.

A remote sensing instrument is a perspective sensor. It views a particular ground object at a specific angle with respect to the surface normal or nadir. This angle depends both on the orientation of the object and the orientation of the sensor. Each image recorded by the camera on the photographic emulsion is taken at a different perspective angle. Solar radiation also falls upon surface objects at varying angles of incidence depending on the time of day and the orien-

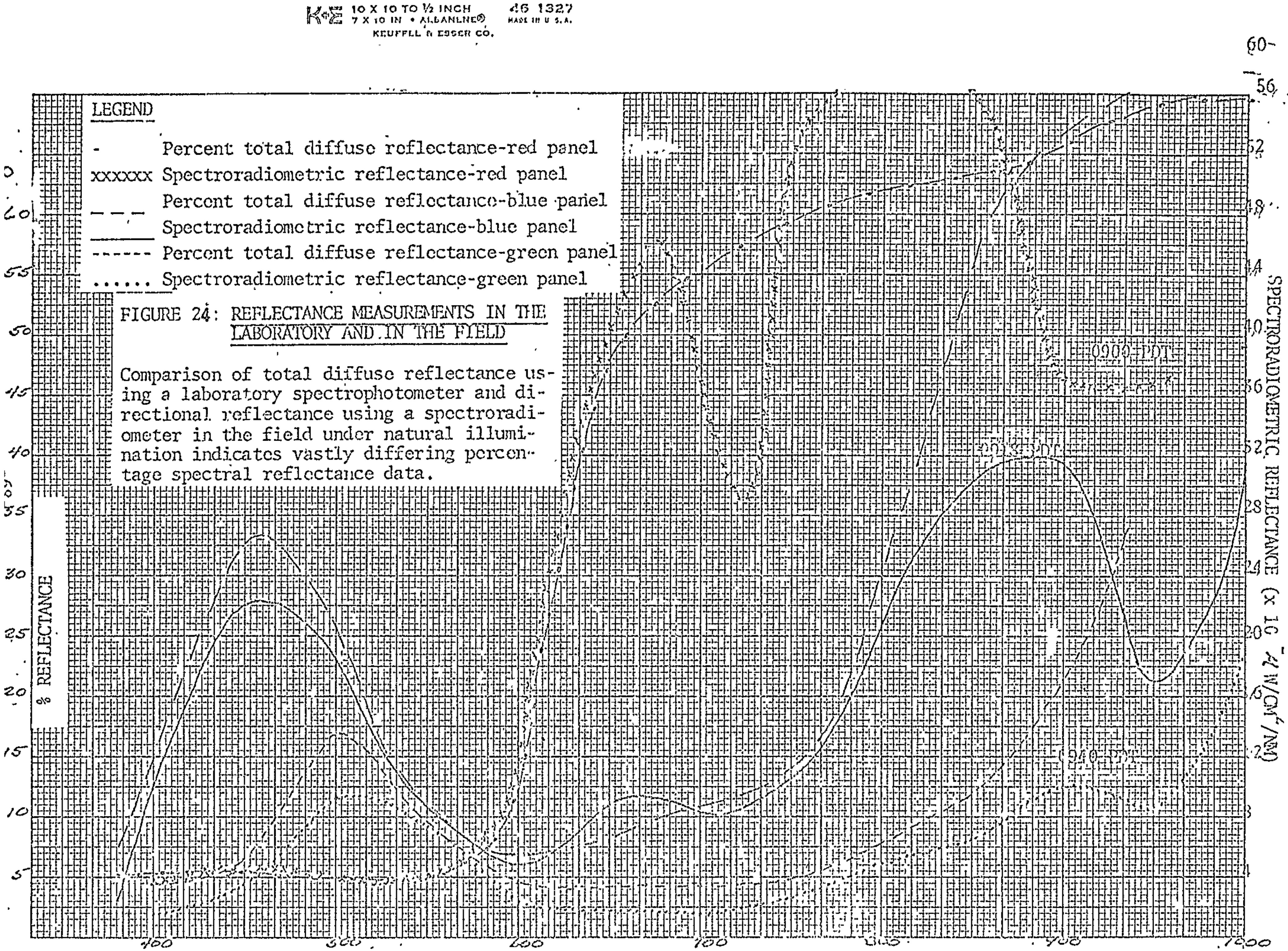


FIGURE 24: REFLECTANCE MEASUREMENTS IN THE LABORATORY AND IN THE FIELD

Comparison of total diffuse reflectance using a laboratory spectrophotometer and directional reflectance using a spectroradiometer in the field under natural illumination indicates vastly differing percentage spectral reflectance data.

tation of the object. The question arises, "what effect do these angular relationships have upon the reflectance spectra of the object as recorded by the sensor?"

Figure 25 demonstrates this important and unresolved problem. Three grey scale panels having nominal reflectance values of 64, 32 and 16 percent were placed on the ground at Davis, California on 30 July 1967. The surface of the panels was textured to minimize specular reflectance from the surface. Simultaneous measurements were made of the spectral distribution of the incident sunlight and the reflectance spectra of the panels. The reflection spectroradiometer was oriented 90 degrees to the incident light in order to eliminate any possibility of specular reflection from the panel surface from being measured.

In order to remove the effects of the spectral distribution of the solar radiation, reflectance data were normalized to a percentage of that incident at each wavelength as follows:

$$\frac{\text{Reflection } (w/cm^2/nm)}{\text{Incident } (w/cm^2/nm)} \times 100$$

What is shown then in Figure 25 is the non-lambertian spectral reflectance of the three panels under identical conditions. It can be seen that at 425 nanometers the reflectance is six percent greater for the 64 percent panels. At 950 nanometers the 64 percent reflecting panel reflects six percent more than the laboratory values, the 32

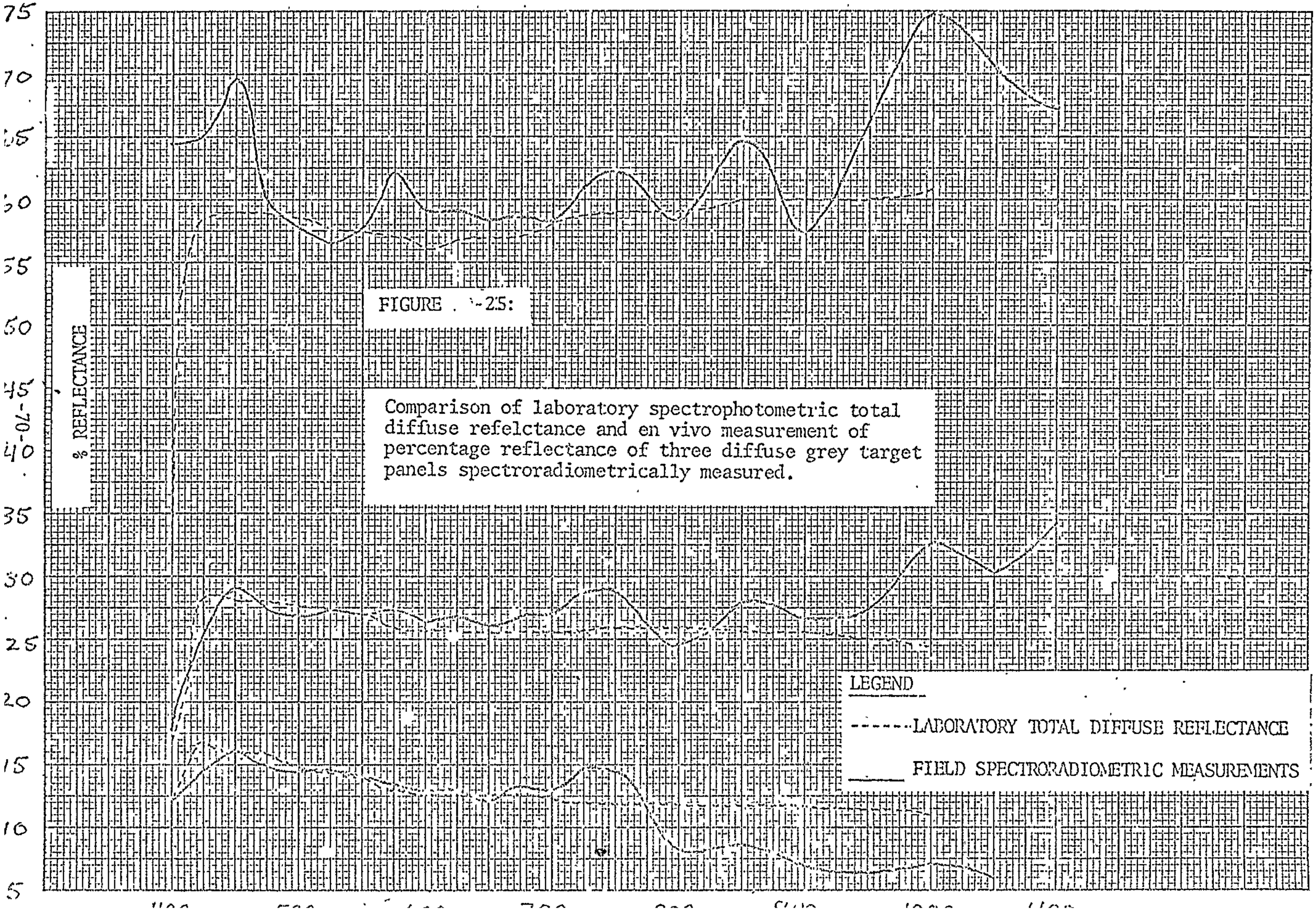


FIGURE -25:

Comparison of laboratory spectrophotometric total diffuse refelctance and en vivo measurement of percentage reflectance of three diffuse grey target panels spectroradiometrically measured.

percent, four percent more and the 16 percent, five percent less.

Thus, the reader can see that even the most carefully constructed, uniformly reflecting target panels do not reflect radiation equally in all angular directions. The reflectance spectra depends on the relative angle of the incident radiation, the orientation of the object as well as the perspective angle of the sensor.

Figure 26 presents a comparison of all three methods of measuring the reflectance spectra for the nominal 32 percent reflectance grey scale target. From this plot it can be seen that the camera sees quite a different target characteristic then one would suppose to be the case from the laboratory spectrophotometric data.

4.3 The Color of Ground Objects Under Natural Illumination

The perceived color of ground objects is a function which is known to depend at least on the spectra of the illuminating light and the reflectance characteristics of the surface structure of the object. However, identical colors can be perceived for the same object under an infinite variety of illuminants and refletance characteristics. For instance, under Luminance C sunlight, the color of a yellow filter (Wratten 12) can be identically matched by the additive mixture of light through a green filter (Wratten 74) and a red filter (Wratten 25) even though the latter two filters transmitt no light at 575 nanometers which is the wavelength described as yellow.

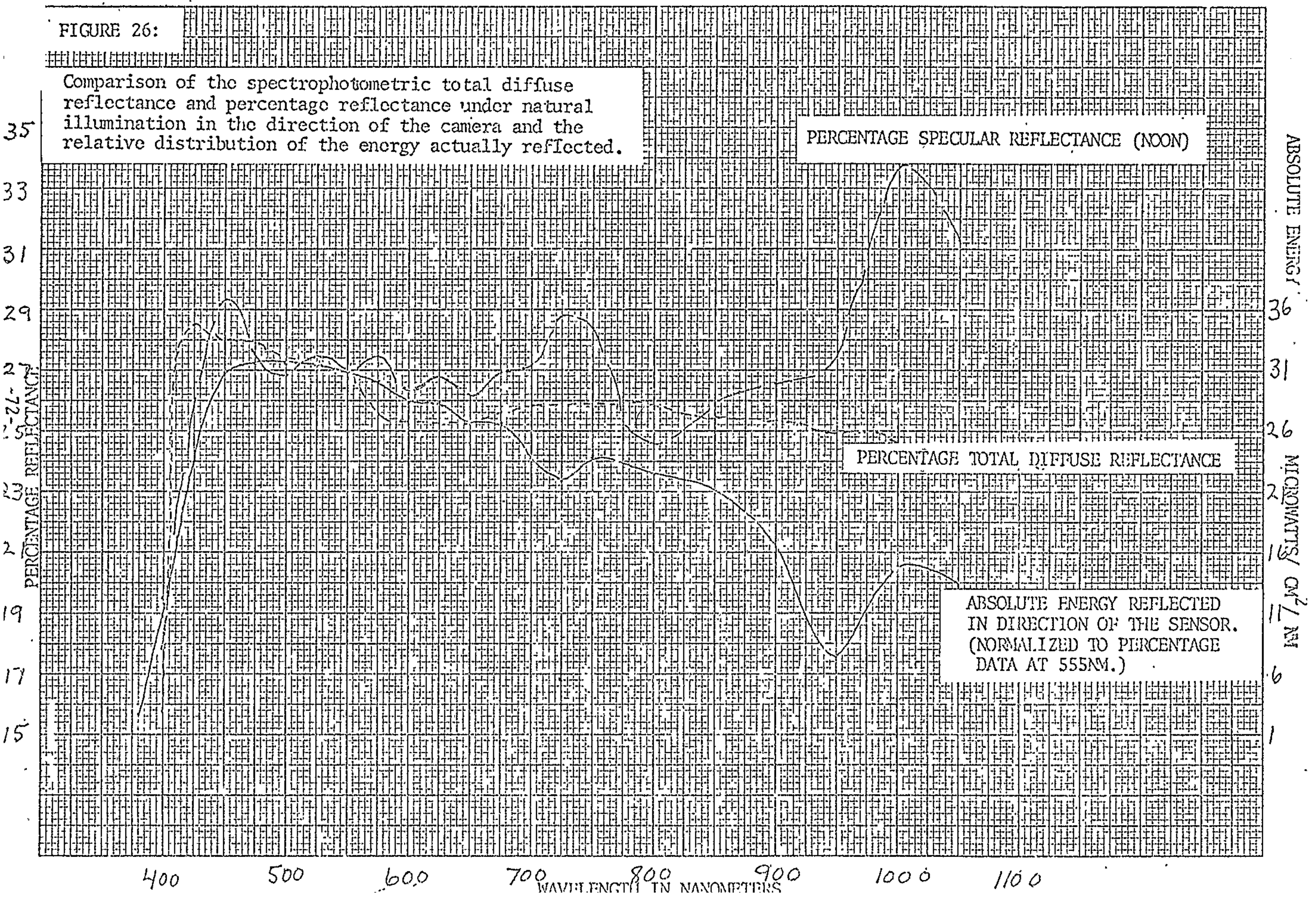
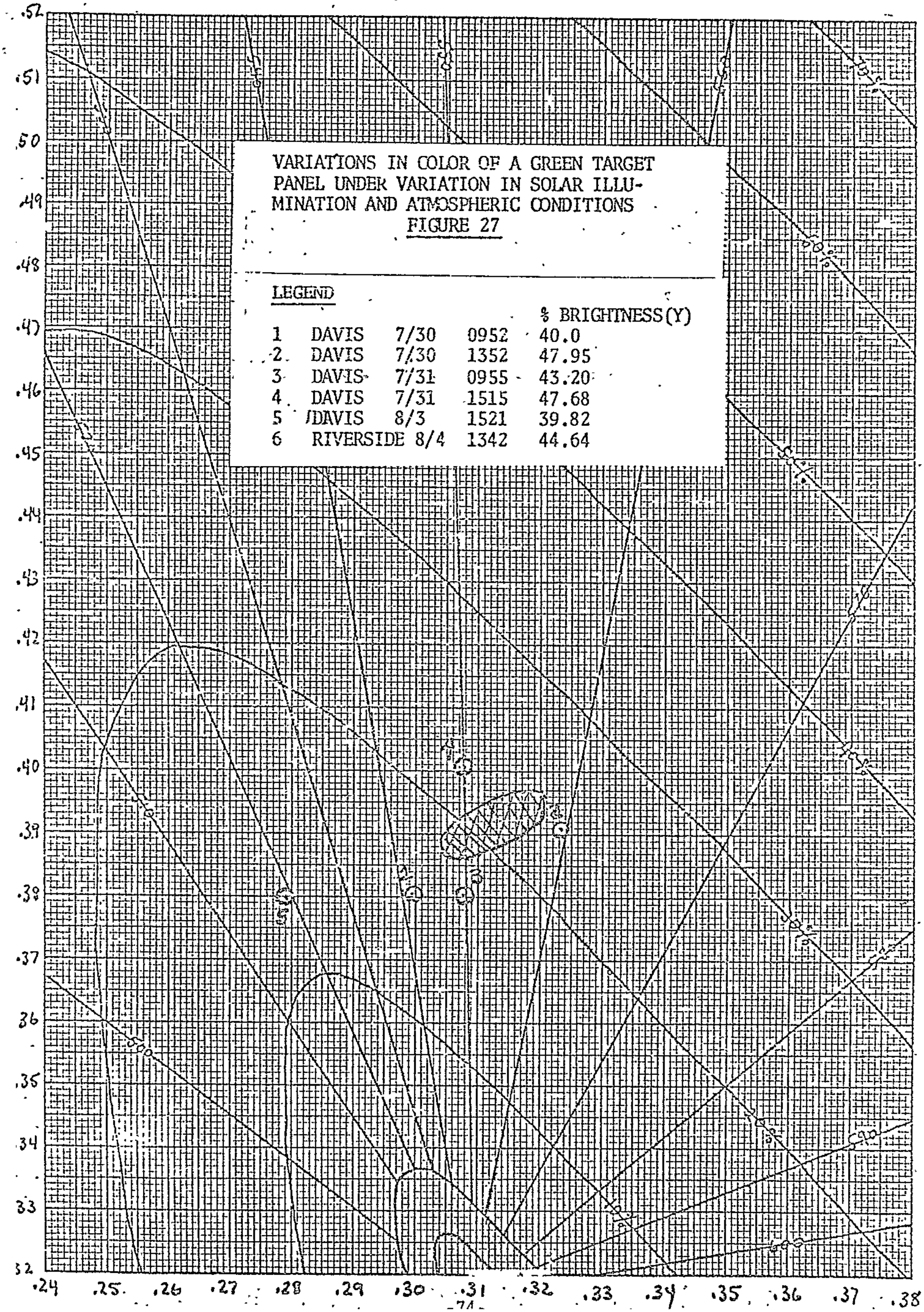


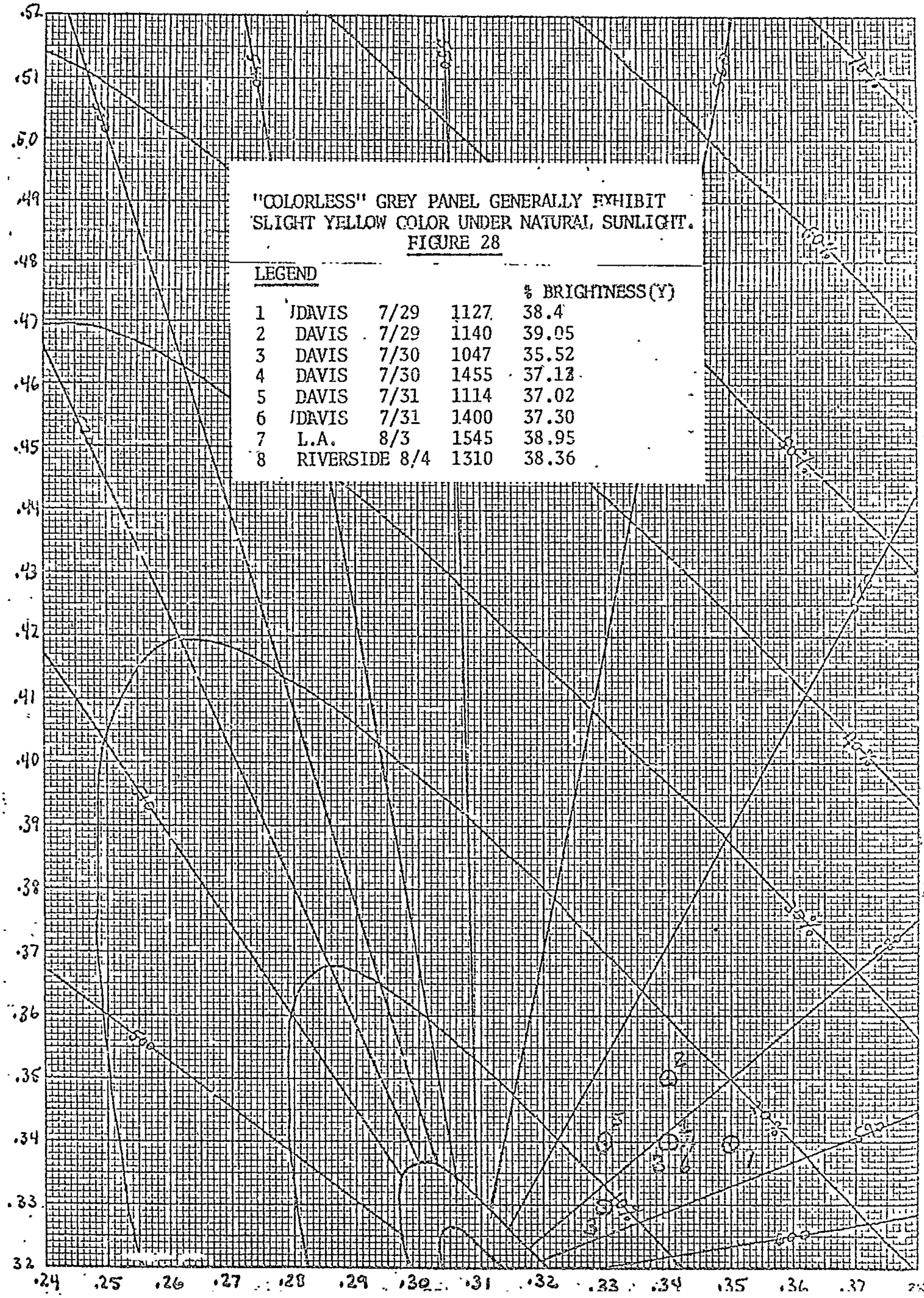
FIGURE 26: Comparison of the spectrophotometric total diffuse reflectance and percentage reflectance under natural illumination in the direction of the camera and the relative distribution of the energy actually reflected.

The consequences of this lack of uniqueness between color and spectra is critical for multispectral color photography as it is for photography using color films. The color of an image can only be used to differentiate objects if (1) the spectra of the objects have been obtained and taking filters chosen appropriately and (2) the spectral distribution of the illuminant is known.

Variations in the color of a green target panel as a function of different conditions of solar illumination between 29 July and 4 August 1967 is shown in Figure 27. By measuring the distribution of the illuminant, and correcting it to a constant value, the colors of the panels can all be placed within the chromaticity coordinates shown in the cross-hatched circle in Figure 27.

Figure 28 shows a similar condition also exists for a achromatic (colorless) grey scale target panel. The apparent dominant wavelength of 580 nanometers indicates that the targets have generally a slight yellow color under natural illumination when measured with reference to the International Standard Luminance C.


VARIATIONS IN COLOR OF A GREEN TARGET PANEL UNDER VARIATION IN SOLAR ILLUMINATION AND ATMOSPHERIC CONDITIONS
FIGURE 27
LEGEND
% BRIGHTNESS(Y)
1 DAVIS 7/30 0952 40.0
2 DAVIS 7/30 1352 47.95
3 DAVIS 7/31 0955 43.20
4 DAVIS 7/31 1515 47.68
5 DAVIS 8/3 1521 39.82
6 RIVERSIDE 8/4 1342 44.64
.52 .51 .50 .49 .48 .47 .46 .45 .44 .43 .42 .41 .40 .39 .38 .37 .36 .35 .34 .33 .32
.24 .25 .26 .27 .28 .29 .30 .31 .32 .33 .34 .35 .36 .37 .38



"COLORLESS" GREY PANEL GENERALLY EXHIBIT SLIGHT YELLOW COLOR UNDER NATURAL SUNLIGHT.

FIGURE 28

SECTION 5

THE RESULTS OF THE EXPERIMENT

Herein are examined the photographic results of the experiment. In general, a comparative methodology is used to analyze the photographic imagery which consists of relating colorimetric measurements of images on both multiband color and subtractive color films. However, the reader will note that this procedure may be modified occasionally depending on the particular situation encountered at a test site, the needs of the environmental discipline and the significance of the results obtained. Figure 29 shows the geographic location of the NASA agriculture, forestry, geographic and geology test sites that were used in this experiment.

The technique used to evaluate the images obtained during the experiment and which are interpreted by "user" scientists is that of analytical color measurement. The chromaticity coordinates of identical images on the multispectral additive color screen and in the subtractive color films are measured. These color signatures are compared to ground measurements. In those instances where false color space has been created, the uniqueness of the image color obtained for ground objects (such as safflower, milo, corn, etc.) has been measured as both functions of spatial, temporal or environmental variables.

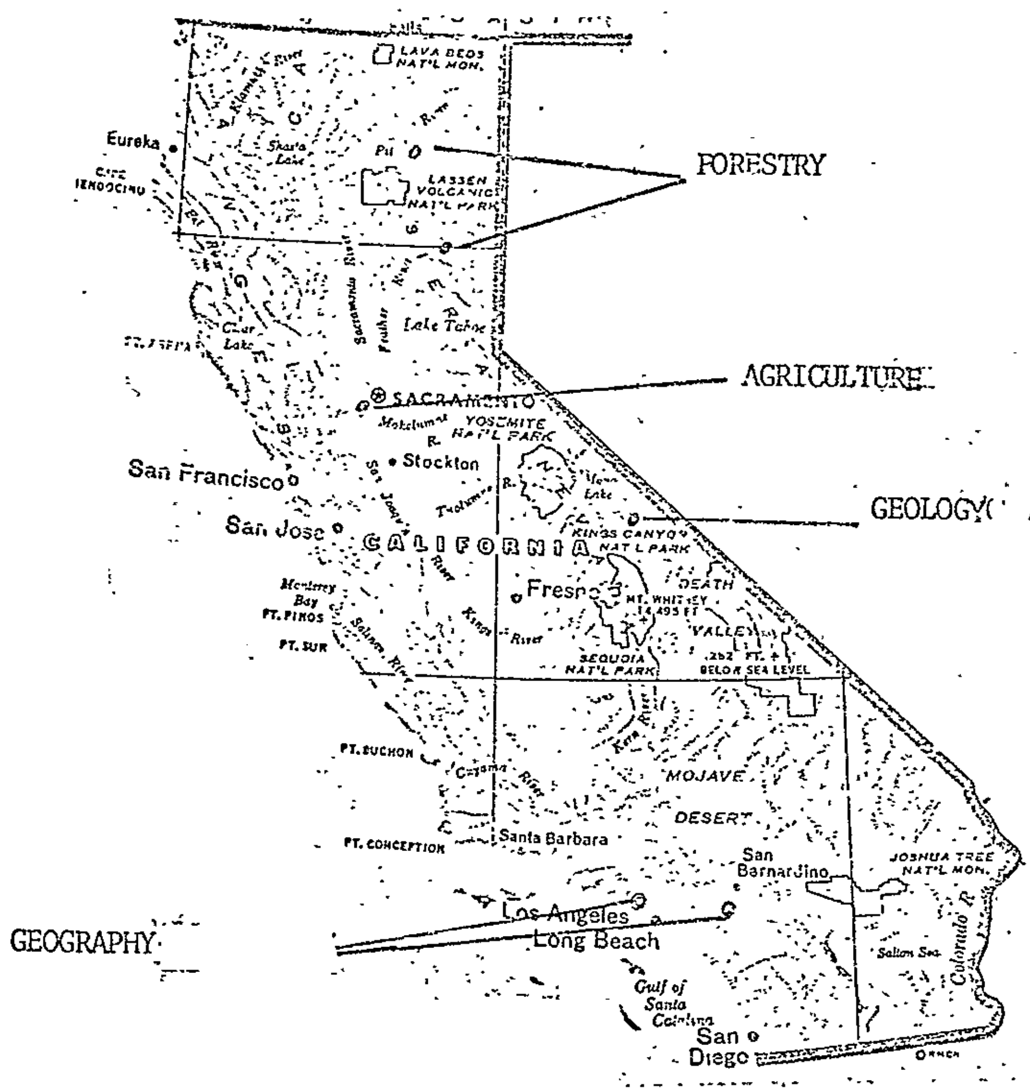


FIGURE -29

LOCATION OF THE NASA TEST SITES IN CALIFORNIA

This methodology of analytical measurement of the image structure is used to establish the accuracy, reproducibility and uniqueness of the image forming capabilities of multiband and conventional color photography. It must be emphasized in the case of the images produced by multispectral color photography that all differences are due to the ability of the camera to adjust exposure independently in each spectral band and the capabiltiy of the viewer to alter the color space to suit the needs of the interpreter. The camera filtration was not selected on any a priori knowledge of spectrophotometric characteristics of the ground objects, the multsipectral camera filters being chosen to approximate the spectral sensitivity of the color films that were used.

5.1 Agriculture

The agricultural test site was located at the Agricultural Experimental Test Station, University of California, Davis, California. The geographic location is shown in Figure 31.

The photography was taken between 28 and 31 July 1967. Figure 32 shows four black and white positive reproductions of multispectral photography taken over the test site at 28,000 feet. The reader will notice that the images on these four photographs are in exactly the same spatial location on each photo. The only difference being the tone or density of the conjugate image on different photos.

FIGURE 30

COLORIMETER BEING USED TO MEASURE COLORS PROJECTED ON THE VIEWER SCREEN.

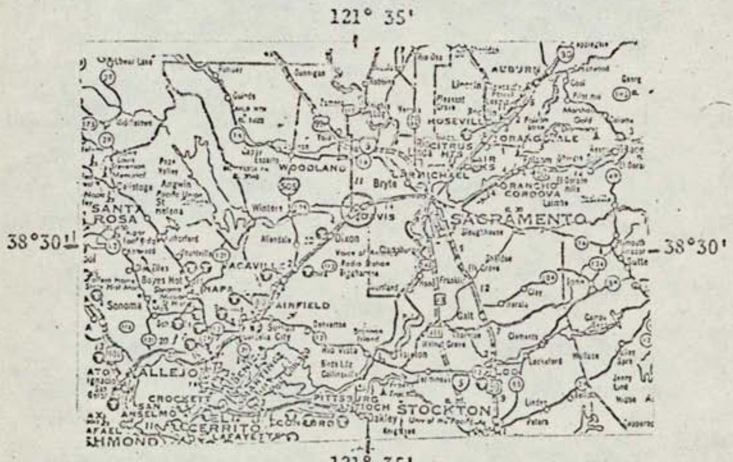


FIGURE 31

GEOGRAPHICAL LOCATION OF AGRICULTURAL EXPERIMENTAL TEST STATION, DAVIS, CALIFORNIA.

FIGURE 32-A

FIGURE 32-B

FIGURE 32-C

FIGURE 32-D

FOUR POSITIVE REPRODUCTIONS OF INDIVIDUAL BLACK AND WHITE MULTISPECTRAL PHOTOGRAPHS TAKEN OVER THE AGRICULTURAL EXPERIMENTAL STATION AT DAVIS, CALIFORNIA ON 31 JULY 1967. FROM TOP TO BOTTOM: BLUE, GREEN, RED AND INFRARED BANDS. THESE PHOTOS WERE TAKEN AT EXACTLY THE SAME TIME BY THE FOUR LENS MULTISPECTRAL CAMERA. THE SPATIAL LOCATION OF ALL IMAGES IS IDENTICAL ON EACH PHOTO WITH RESPECT TO THE PRINCIPAL POINT. THE DENSITY OF IMAGES DEPENDS ON THE SPECTRAL BAND.

FIGURE 32

The additive color viewer superimposed the red, green and blue spectral photos to form a true color reproduction of the ground which is shown in Figure 33. The ground target panels are shown in this photograph. The Ektachrome (8442) photograph is also shown in the center of this figure. This photograph was taken at exactly the same time as the multispectral photograph above it. The photo at the bottom of the Figure 33, shows the ground target which consisted of the four colors: green, yellow, blue and red. To the right of the target is a five step grey scale.

The color of the panels was measured within plus or minus 1/2 hour of the time the photography was taken. The chromaticity coordinates of the ground measurements of the color panels is shown in Figure 34. The color of the ground panel images was measured on the Aerial Ektachrome film and is also shown in this figure. The color of the multispectral reproduction shown at the top of Figure 33 was adjusted to match as closely as possible the colors of all four ground targets in a single screen presentation. For the particular characteristics of photographic reproduction of both the negative and positive which were projected, it was possible to match the chromaticity coordinates relative to the ground chromaticity coordinates as shown in Figure 34. From the analytical description of colors shown in this figure, we see that it was possible to obtain a much closer match to the ground colors using the additive manipulation of the color space in the additive sy-

FIGURE 33-A

FIGURE 33-B

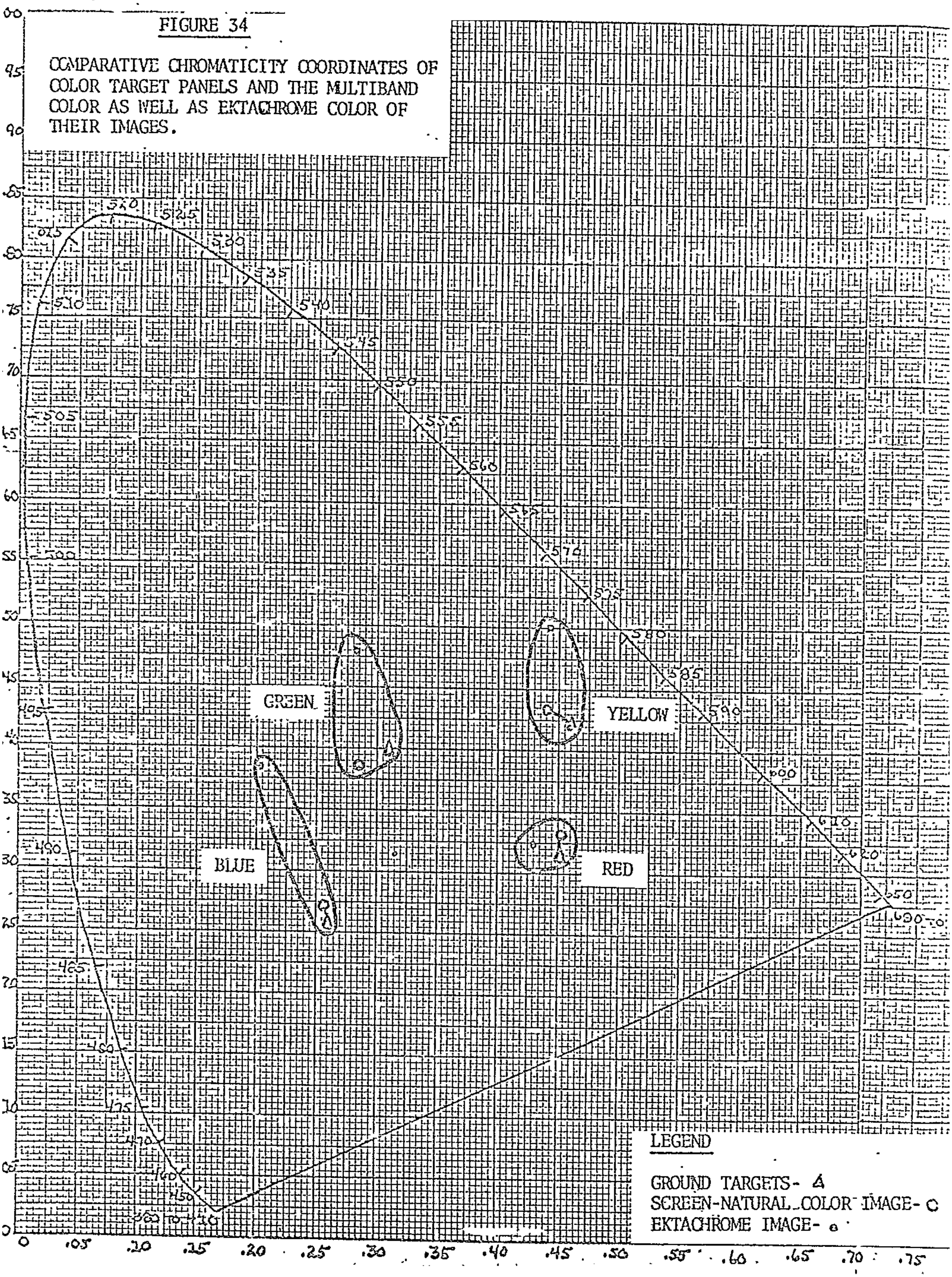
FIGURE 33-C

TOP PHOTO IS A MULTISPECTRAL TRUE COLOR RENDITION COPIED FROM THE VIEWER SCREEN IN WHICH THE BLUE, GREEN AND RED MULTISPECTRAL POSITIVES ARE PROJECTED EACH IN THE SAME COLOR. IN THE CENTER IS AN AERIAL EKTACHROME P PHOTO TAKEN AT THE SAME TIME USING AN OPTICAL SYSTEM IDENTICAL TO THAT OF THE MULTISPECTRAL CAMERA. THE BOTTOM PHOTO SHOWS THE TARGET ARRAY CONSISTING OF FOUR COLOR TARGET PANELS AND A GREY SCALE.

FIGURE 33

FIGURE 34

COMPARATIVE CHROMATICITY COORDINATES OF COLOR TARGET PANELS AND THE MULTIBAND COLOR AS WELL AS EKTACHROME COLOR OF THEIR IMAGES.



stem compared to the particular subtractive color film used.

The spectral reflectance of the color panels is shown in Figure 35. These measurements were not taken at exactly the same time the photography was obtained, however, they do give some indication of the relative reflectance spectra of the targets under natural illumination.

Figure 36 shows chromaticity coordinates of four ground objects measured from the multispectral additive color viewer which were shown at the top of Figure 33. The colors have been measured and plotted for ground objects of alfalfa, barley, bare soil, and tomatoes. The tomatoes exhibited three different growth conditions, being: newly sprouted plants; plants that were flowering and plants developing tomatoes (approaching maturity). The images of the same objects measured on Aerial Ektachrome are shown in Figure 37. It can be seen that the objects occupy entirely different chromaticity coordinates on Ektachrome film as compared to the additive color rendition. Figure 38 compares the chromaticity coordinates of the four ground objects as they appear on the multiband color image and the Ektachrome image. The fidelity of color reproduction, which from an examination of Figure 34 is quite close to that of the ground in the multispectral additive image, is much less faithfully reproduced by the Ektachrome film. This is particularly true in the case of alfalfa and newly planted tomatoes.

Figure 39 shows a comparison of four multispectral false color ren-

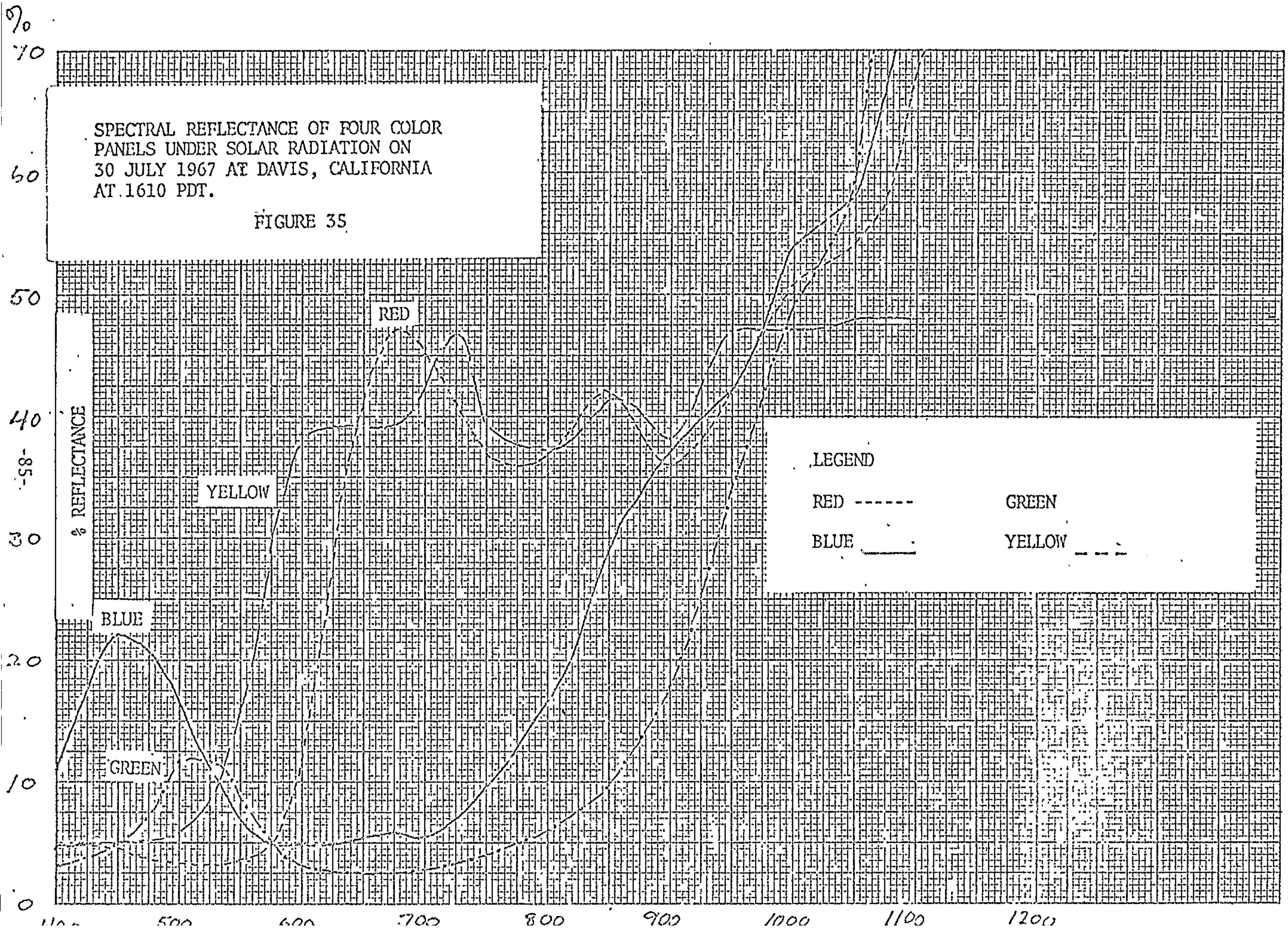

SPECTRAL REFLECTANCE OF FOUR COLOR PANELS UNDER SOLAR RADIATION ON 30 JULY 1967 AT DAVIS, CALIFORNIA AT 1610 PDT.
%
% REFLECTANCE
RED
YELLOW
BLUE
GREEN
LEGEND
RED ------
GREEN
BLUE ____
YELLOW _ _ _
70
60
50
40
30
20
10
0
500
600
700
800
900
1000
1100
1200

FIGURE 35

FIGURE 36

CHROMATICITY COORDINATES OF AGRICULTURAL FEATURES EXHIBITED BY THE MULTISPECTRAL TRUE COLOR PRESENTATION.

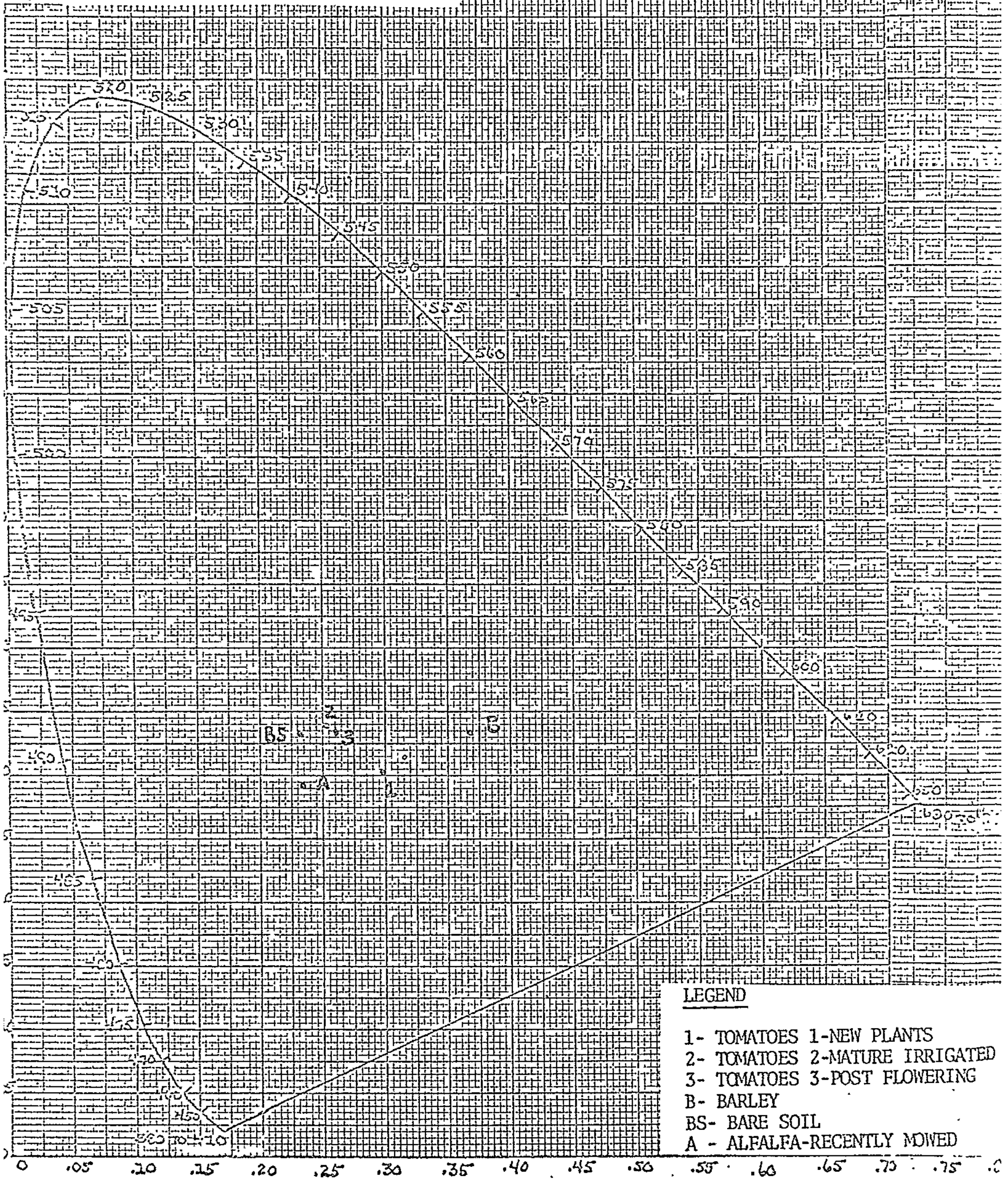
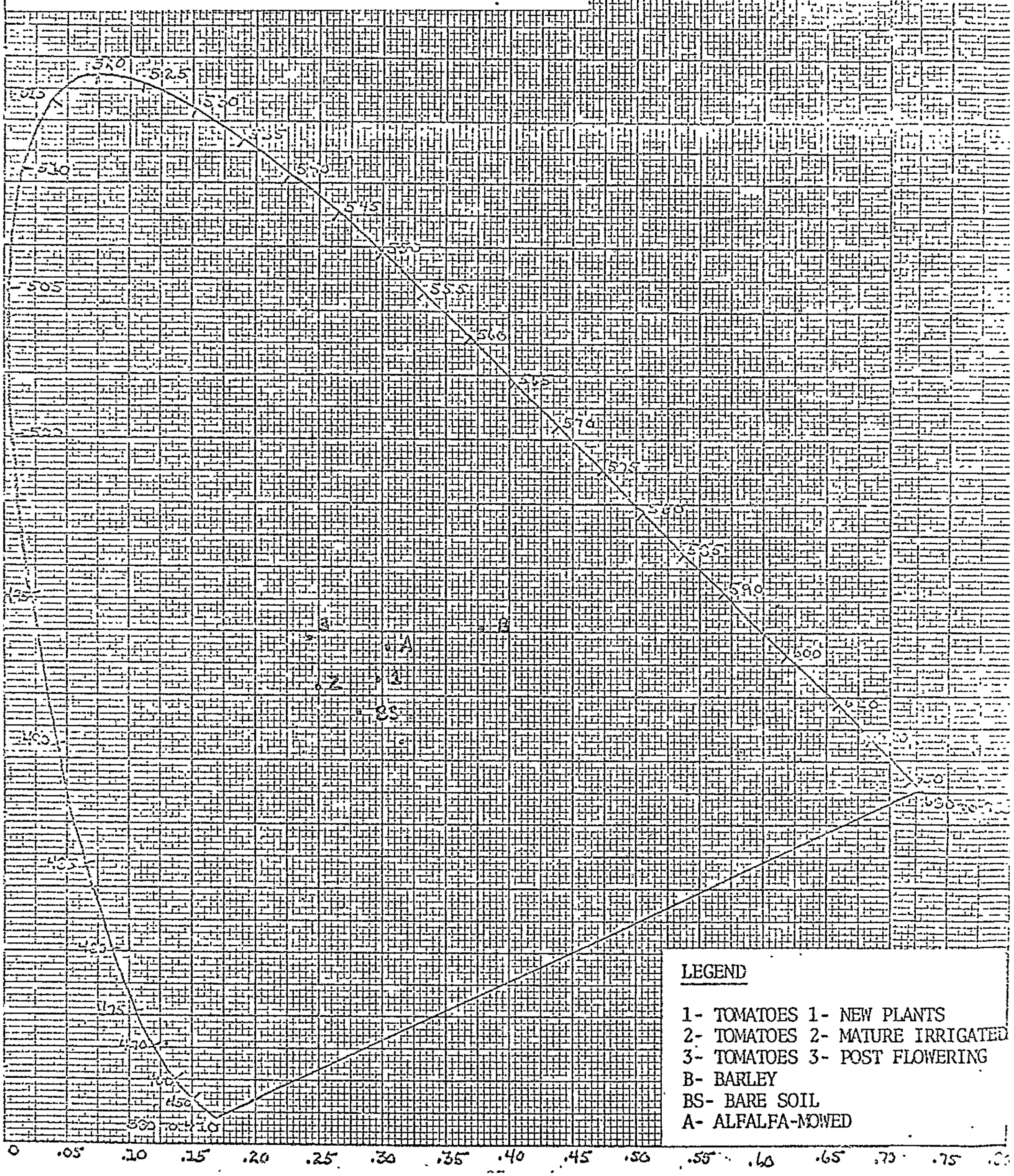


FIGURE 37

CHROMATICITY COORDINATES OF AGRICULTURAL FEATURES EXHIBITED BY AERIAL EKTACHROME.



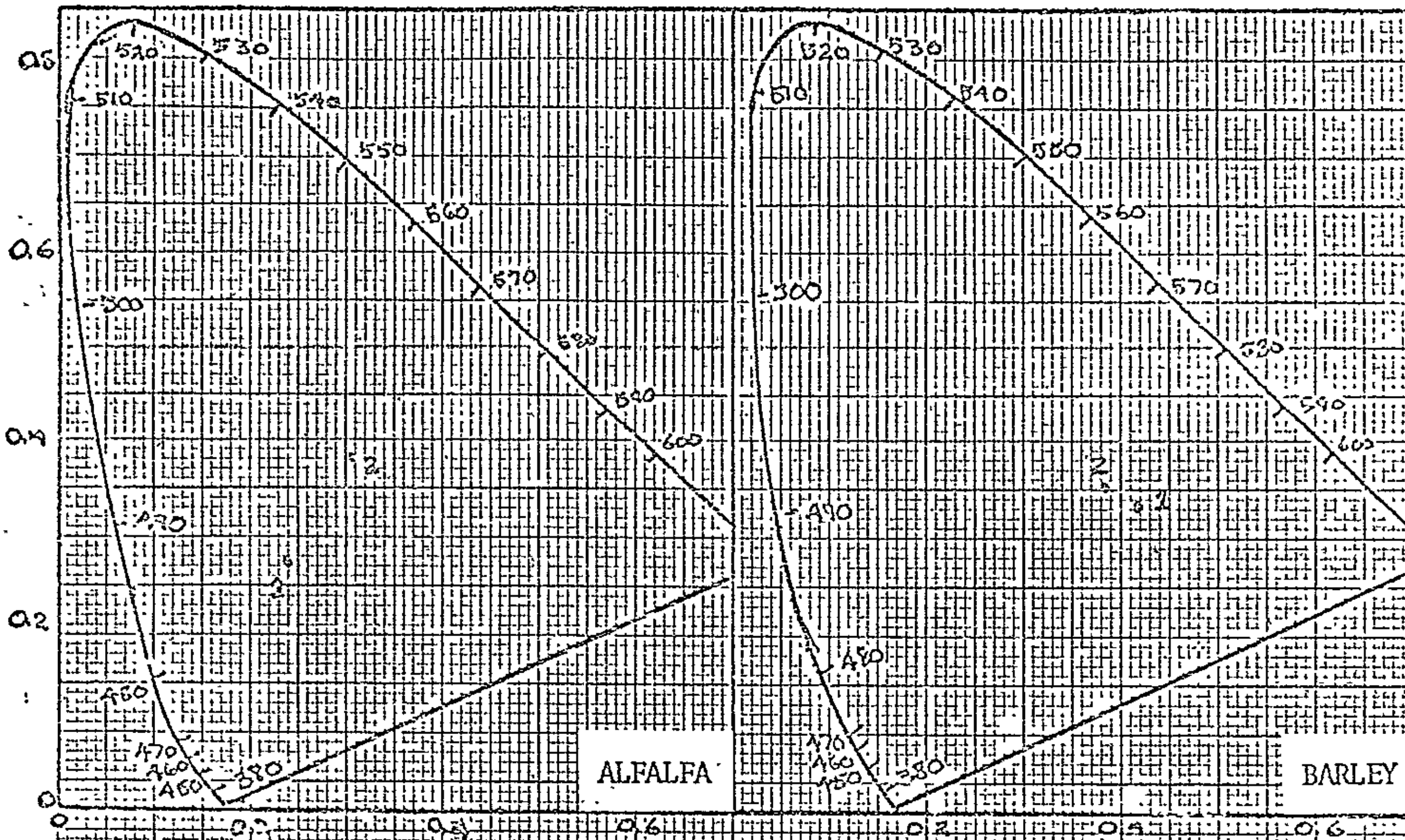
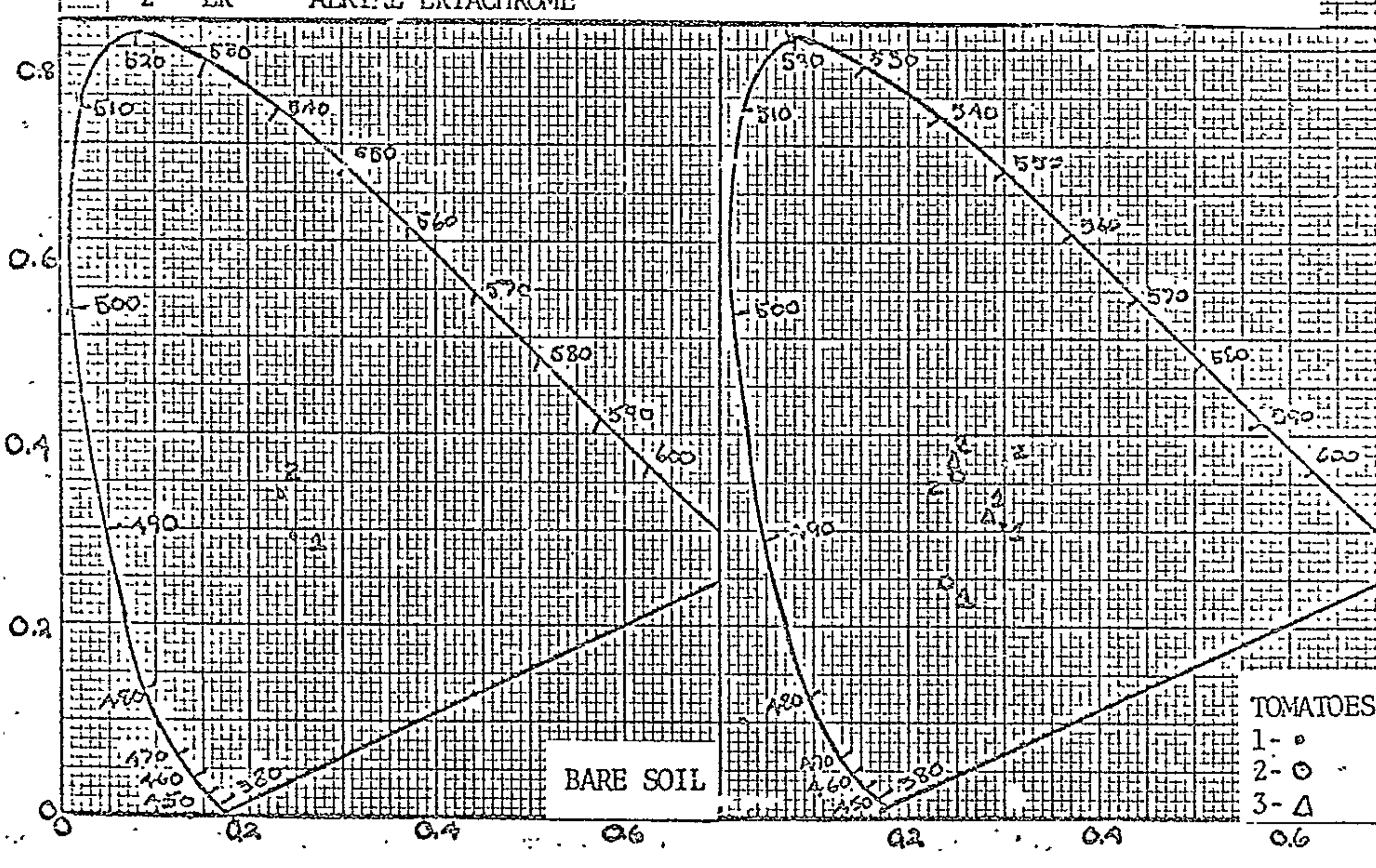


FIGURE 38

COMPARATIVE CHROMATICITY COORDINATES OF THE IMAGES OF AGRICULTURAL FEATURES AS RECORDED BY MULTISPECTRAL TRUE COLOR RENDITION AND AERIAL EKTACHROME

LEGEND

1 - C-1-1 MULTISPECTRAL TRUE COLOR
2 - EK AERIAL EKTACHROME



ditions including Aerial Ektachrome Infrared (8443). The top three false color multispectral renditions have been created by addition of the infrared band shown in Figure 32 with the green and red bands and varying the hue and saturation of the color space to produce the effects shown in Figure 39. The Ektachrome Infrared photo shown at the bottom of the page was taken at exactly the same time as were the top three photos.

Figure 40 shows the chromaticity of seven ground objects as they appear in each of these four photographs. This Figure shows us the chromatic color differentiating capabilities of each of the renditions. For instance, using multispectral rendition A, it was possible to chromatically separate barley, milo, alfalfa, flowering tomatoes and corn from each other quite well. Multispectral rendition B allowed chromatic differentiation of bare soil from flowering tomatoes quite well but milo and alfalfa are close to each other in their color. Rendition C in the lower left of the figure separates many of the ground objects well with the exception of corn, alfalfa and milo which are quite close chromatically although the interpreter can more easily identify their color differences because of their position in the blue part of the chromaticity diagram. The chromaticity coordinates of these objects are shown for Aerial Ektachrome Infrared in the lower right of Figure 40. Here we see a general bunching of the colors in the blue-magenta part of the diagram and also that the colors are not nearly as well separated as they were in any-

MULTISPECTRAL RENDITION A
Green band projected as blue
Red band projected as breen
Infrared band projected as red

MULTISPECTRAL RENDITION B
Green band projected as blue
Red band projected as red
Infrared band projected as green

MULTISPECTRAL RENDITION C
Green band projected as red
Red band projected as green
Infrared band projected as blue

AERIAL EKTACHROME INFRARED PHOTOGRAPH.

COMPARISON OF MULTISPECTRAL FALSE COLOR RENDITIONS WITH CONVENTIONAL AERIAL EKTACHROME INFRARED FILM IMAGES OF SOME AGRAICULTURAL CROPS AT 1617 PDT, 31 JULY 1967. THE TOP THREE PHOTOS ARE MULTISPECTRAL FALSE COLOR RENDITIONS AND THE BOTTOM, AERIAL EKTACHROME INFRARED (8443) TAKEN SIMULTANEOUSLY WITH THE MULTISPECTRAL PHOTOS.

FIGURE 39

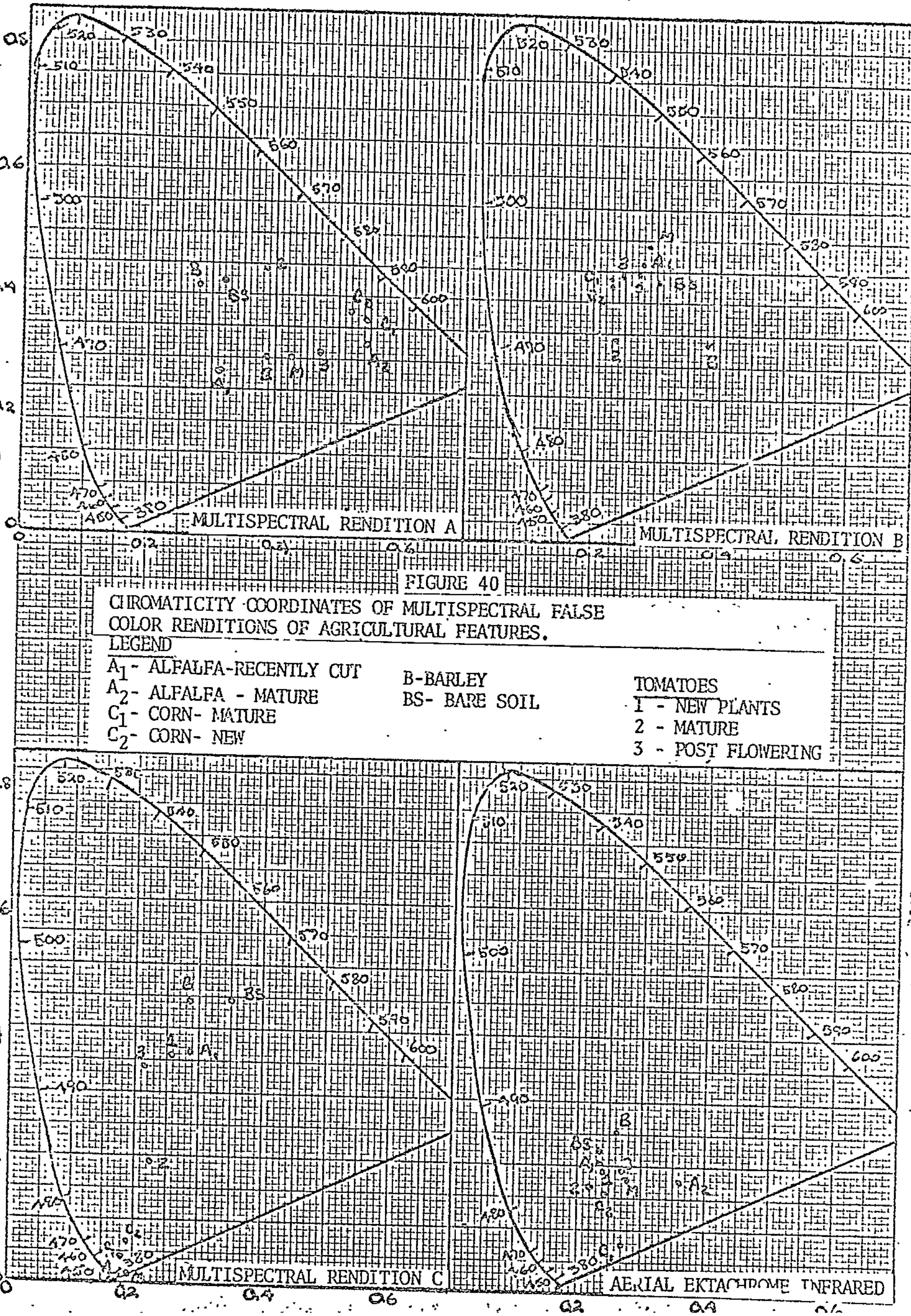


FIGURE 40

CHROMATICITY COORDINATES OF MULTISPECTRAL FALSE COLOR RENDITIONS OF AGRICULTURAL FEATURES.

LEGEND

A_1 - ALFALFA-RECENTLY CUT
A_2 - ALFALFA - MATURE
C_1 - CORN- MATURE
C_2 - CORN- NEW

B-BARLEY
BS- BARE SOIL

TOMATOES
1 - NEW PLANTS
2 - MATURE
3 - POST FLOWERING

of the above multiband renditions.

Figure 41 shows the relative position of similar crops in the four false color renditions discussed previously. Here it can be seen that it is possible to position the colors of objects in the color solid depending on the method of projection the false color multiband photography or by using false color subtractive films.

Figures 43, 44 and 46 are quite significant in that they show the ability of multiband additive color techniques to establish the chromatic characteristics of images relating to the same ground object as a function of three variables: altitude, time of day and the spatial-spectral characteristics of the particular object. Figure 42 shows the false color rendition of an area of the test site in which the green band has been projected as blue, the red band projected as green and the infrared as red. The photo at the top of the Figure 42 was taken at 28,000 feet. The center photo was taken at 15,000 feet and the photo at the bottom of the page at 3,000 feet, all taken on 31 July 1967. The image appears in all photographs as shown by the annotations in the top two photos.

Figure 43 shows the chromaticity ocordiantes of three crops as they appear in each photograph. The crops are safflower, corn and milo. In this figure we see that safflower exhibits a reasonably tight grouping about dominant wavelengths between 550 and 560 nanometers, and milo has

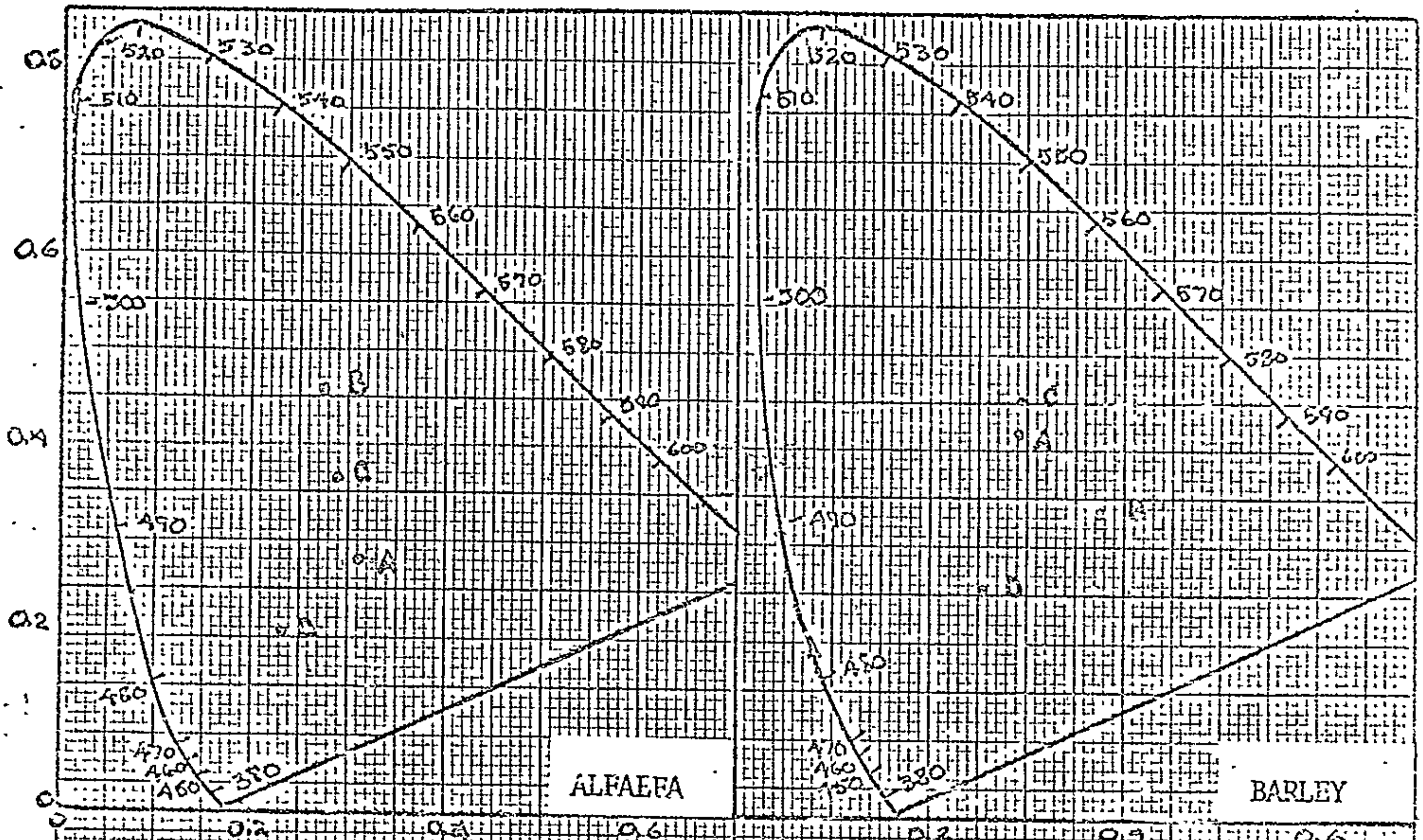


FIGURE 41

CHROMATICITY COORDINATES OF AGRICULTURAL CROPS IN FALSE COLOR MULTISPECTRAL RENDITIONS AND AERIAL EKTACHROME INFRARED.

LEGEND

A- MULTISPECTRAL RENDITION A B- MULTISPECTRAL RENDITION B
C- MULTISPECTRAL RENDITION C D- AERIAL EKTACHROME INFRARED

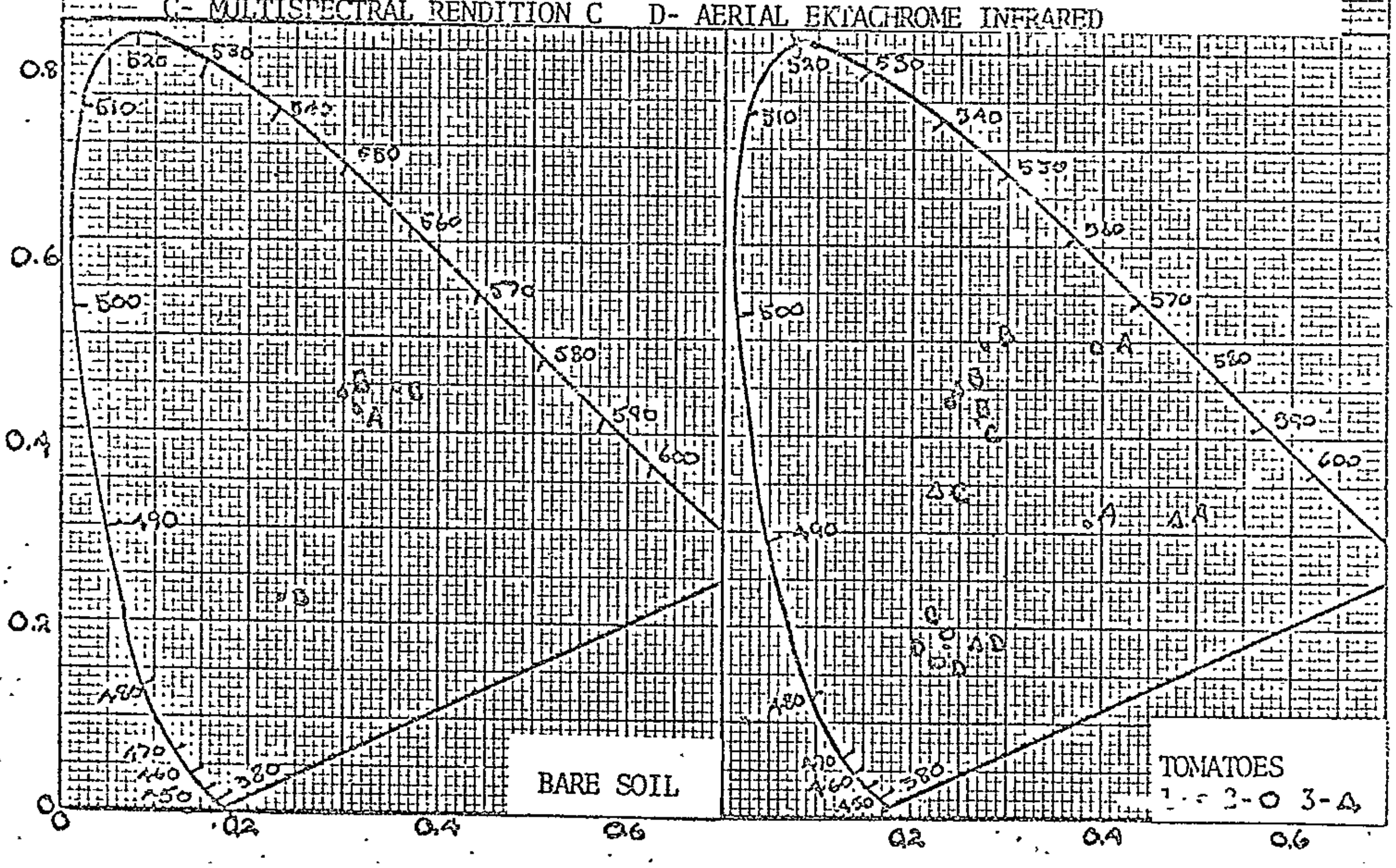


FIGURE 42-A

28,000 FEET

FIGURE 42-B

15,000 FEET

FIGURE 42-C

3,000 FEET

FIGURE 42:
COLOR OF SIGNIFICANT CROPS AS A FUNTION OF BOTH ALTITUDE AND TIME VARIATIONS ON 31, JULY 1967 DAVIS, CALIFORNIA
FALSE COLOR---GREEN PROJECTED AS BLUE
RED PROJECTED AS GREEN
INFRARED PROJECTED AS RED

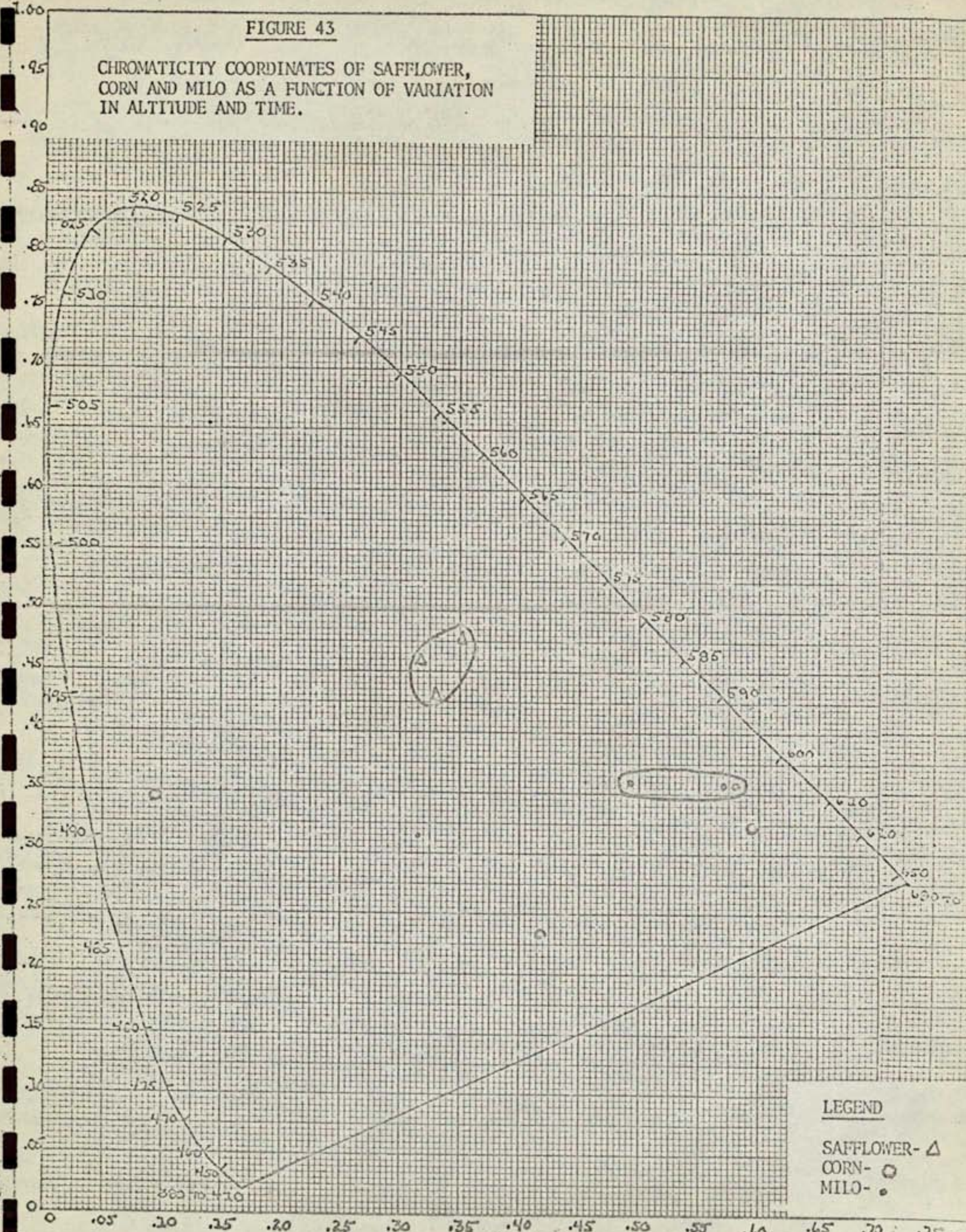


FIGURE 43

CHROMATICITY COORDINATES OF SAFFLOWER, CORN AND MILO AS A FUNCTION OF VARIATION IN ALTITUDE AND TIME.

relatively constant dominant wavelength of 600 nanometers with varying saturation. However, the variation in the colors of corn is of particular significance. Color measurement of all the above images was made using a probe which integrated the light from a 3 1/2 mm diameter circle on the viewer screen. The fact that the spacing in corn is clearly evident in the lower altitudes as the ground is resolved as spaces between the crop rows. However, as altitude increases fewer and fewer of the rows are resolved until at 28,000 feet a relatively homogeneous color is produced not too different from that exhibited by milo.

Figure 44 uses identically the same spectral positives as the previous figure, however the color space has been changed. The green band is projected as red, the red band as blue and the infrared band as green. Figure 45 again shows the chromaticity plot of corn, milo and safflower. However, in this color space, we see considerable overlap between the colors of corn and milo, also this color space minimizes the chromatic effects on the image of the spacing in the corn crop. The color of safflower is different (as seen from Figure 45), because the color measurement was made in the central part of the plot where considerable amount of soil is resolved along with the plants.

A third manipulation of the color space shown in Figure 46 is achieved by projecting the blue band as red, the green band as green and the infrared band as blue. From the color plot shown in Figure 47, we see that the colors of the safflower images at all altitudes and at different

FIGURE 44-A
28,000 FEET

FIGURE 44-B
15,000 FEET

FIGURE 44-C
3,000 FEET

FIGURE 44:

COLOR OF SIGNIFICANT CROPS AS A FUNCTION OF BOTH ALTITUDE AND TIME VARIATIONS ON 31 JULY 1967 DAVIS, CALIFORNIA
FALSE COLOR---GREEN PROJECTED AS RED
RED PROJECTED AS BLUE
INFRARED PROJECTED AS GREEN

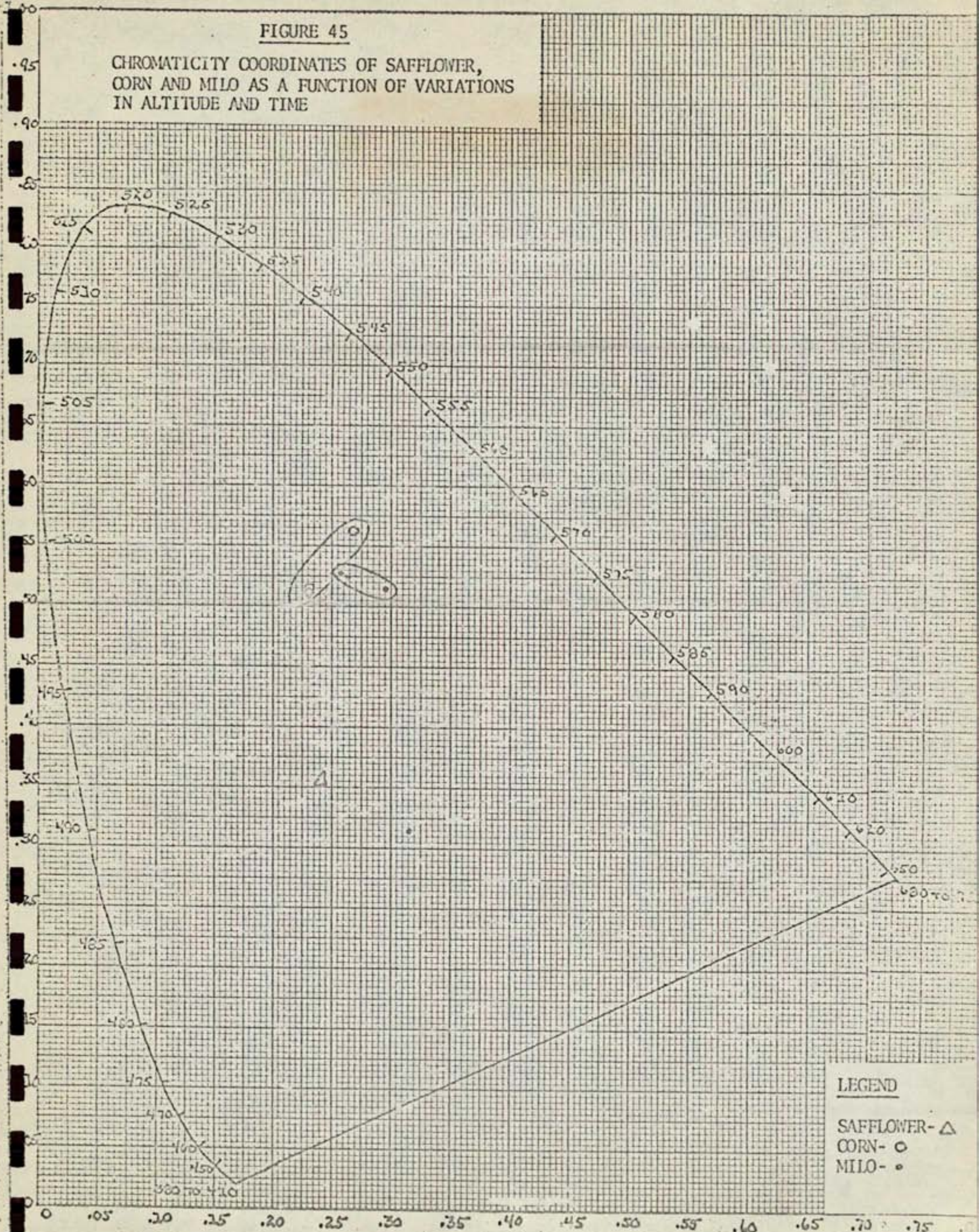


FIGURE 45
CHROMATICITY COORDINATES OF SAFFLOWER, CORN AND MILO AS A FUNCTION OF VARIATIONS IN ALTITUDE AND TIME
LEGEND
SAFFLOWER- △
CORN- ○
MILO- •
520
525
530
535
540
545
550
555
570
580
585
590
600
505
490
485
470
0
.05
.10
.15
.20
.25
.30
.35
.40
.45
.50
.55
.60
.65
.70
.75

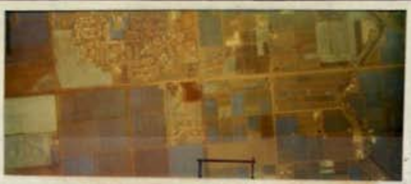


FIGURE 46-A
28,000 FEET

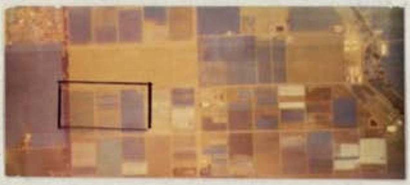


FIGURE 46-B
15,000 FEET

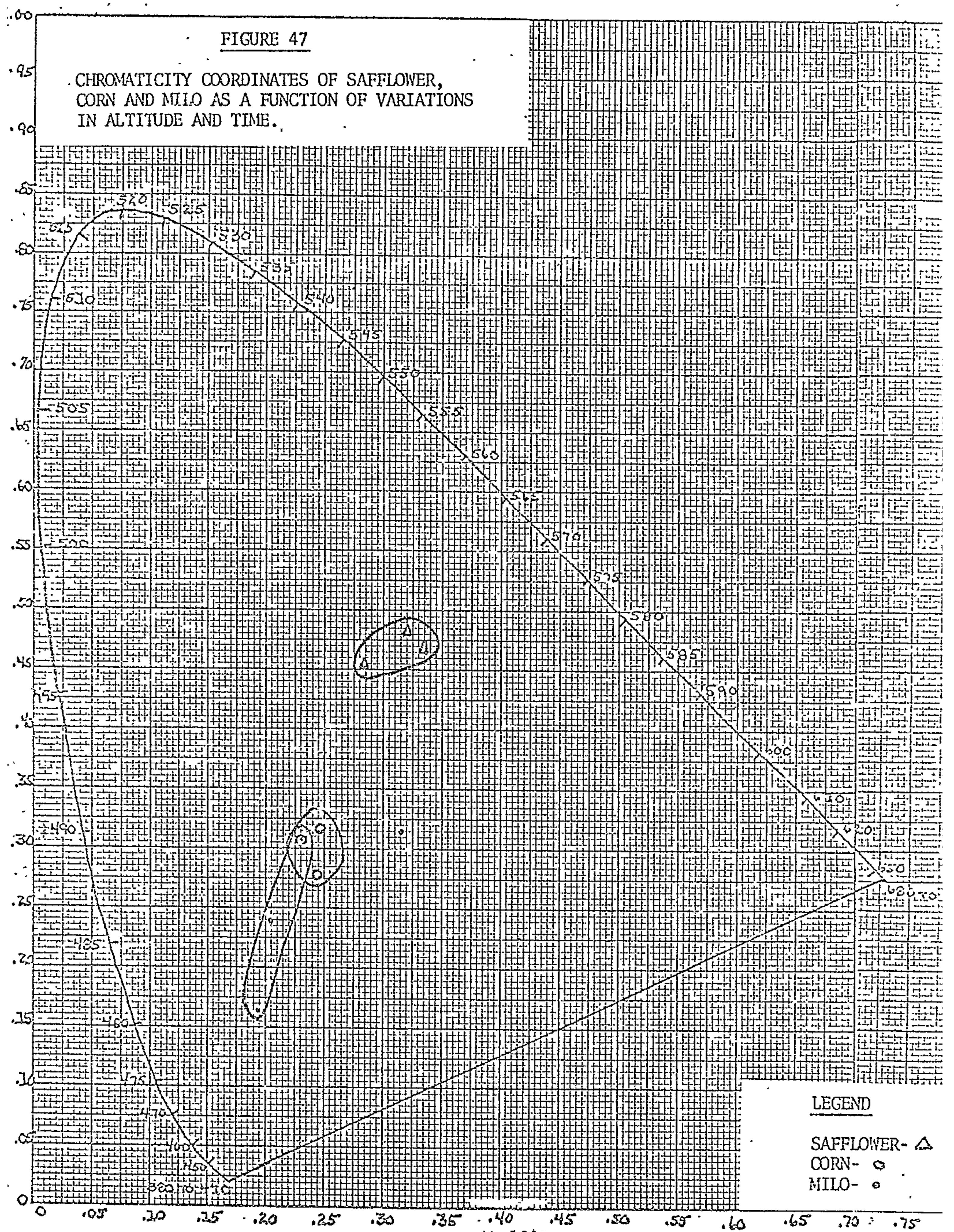
FIGURE 46-C
3,000 FEET

FIGURE 46:

COLOR OF SIGNIFICANT CROPS AS A FUNCTION OF BOTH ALTITUDE AND TIME VARIATIONS ON 31 JULY 1967 DAVIS, CALIFORNIA
FALSE COLOR---BLUE PROJECTED AS RED
GREEN PROJECTED AS GREEN
INFRARED PROJECTED AS BLUE

FIGURE 47

CHROMATICITY COORDINATES OF SAFFLOWER, CORN AND MILO AS A FUNCTION OF VARIATIONS IN ALTITUDE AND TIME.



times are quite closely grouped together, whereas overlap occurs in one instance between milo and corn.

Figure 48 shows the chromaticity coordinates of the colors produced by alfalfa on the low altitude photograph. From this figure the reader can see the transformation of the image color from red to green to blue depending on the color space achieved in projection.

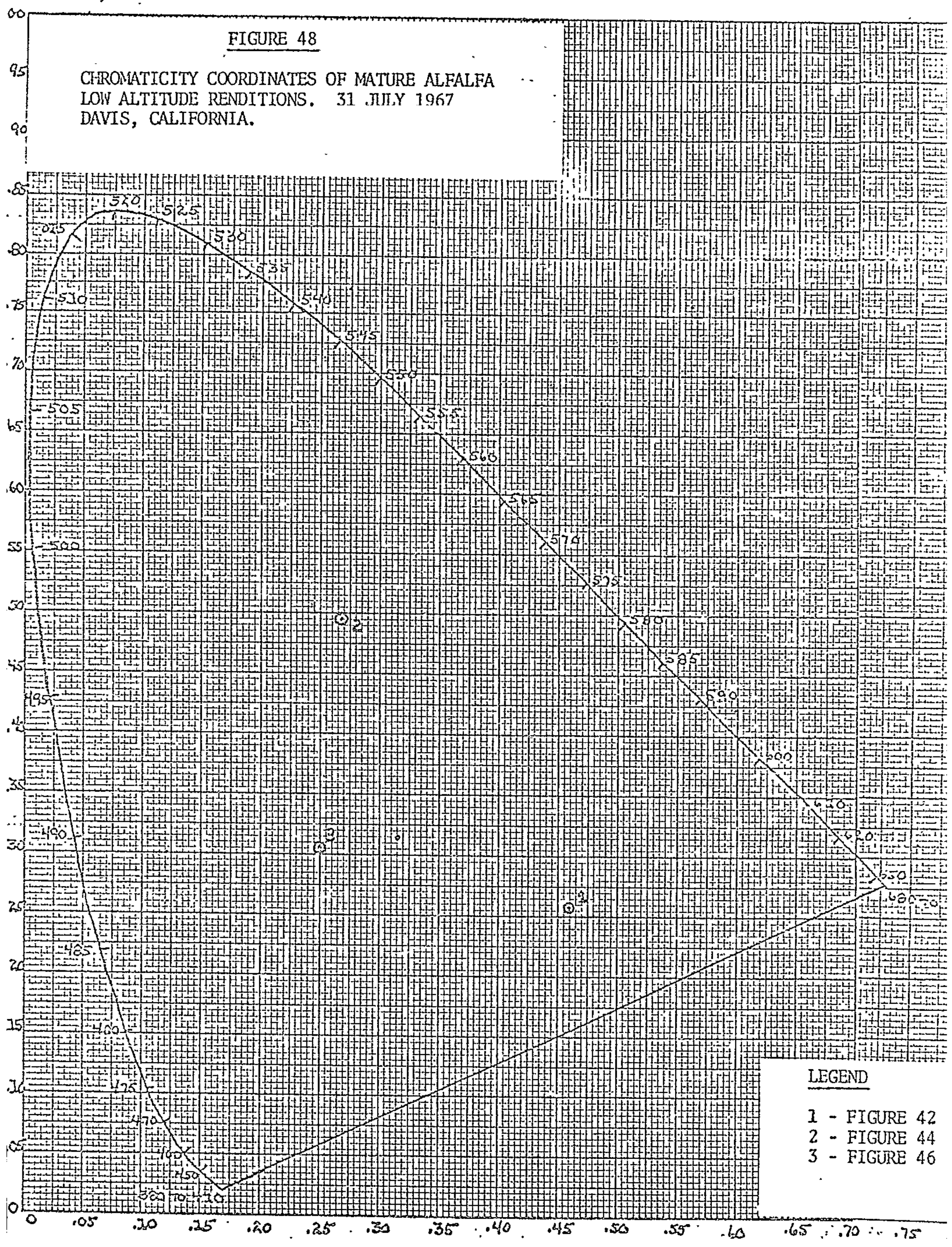
Figure 49 shows the spectral reflectance of three crops, alfalfa, rye and safflower. These data have been spectroradiometrically obtained in the field and the readings corrected to noon sunlight conditions that existed on 31 July 1967. Where very little difficulty is usually encountered in obtaining a spectral-color signature of flowering safflower, it is quite difficult generally, to spectrally differentiate rye and alfalfa. The data presented in this figure indicates that at least under noon illuminating conditions, one might expect to be able to obtain unique color signatures for alfalfa and rye by subdivision of the 700 to 800 nanometers spectral band. The reader will remember that both the multiband filters used in this experiment as well as the infrared film recorded the entire 700-900 band of the near infrared spectrum as a single band.

5.2 Forestry

The Forestry test sites, which were overflown, consisted of two areas: on in the Quincy-Meadow Valley-Bucks Lake area which is generally heavily

FIGURE 48

CHROMATICITY COORDINATES OF MATURE ALFALFA LOW ALTITUDE RENDITIONS. 31 JULY 1967 DAVIS, CALIFORNIA.



LEGEND

1 - FIGURE 42
2 - FIGURE 44
3 - FIGURE 46

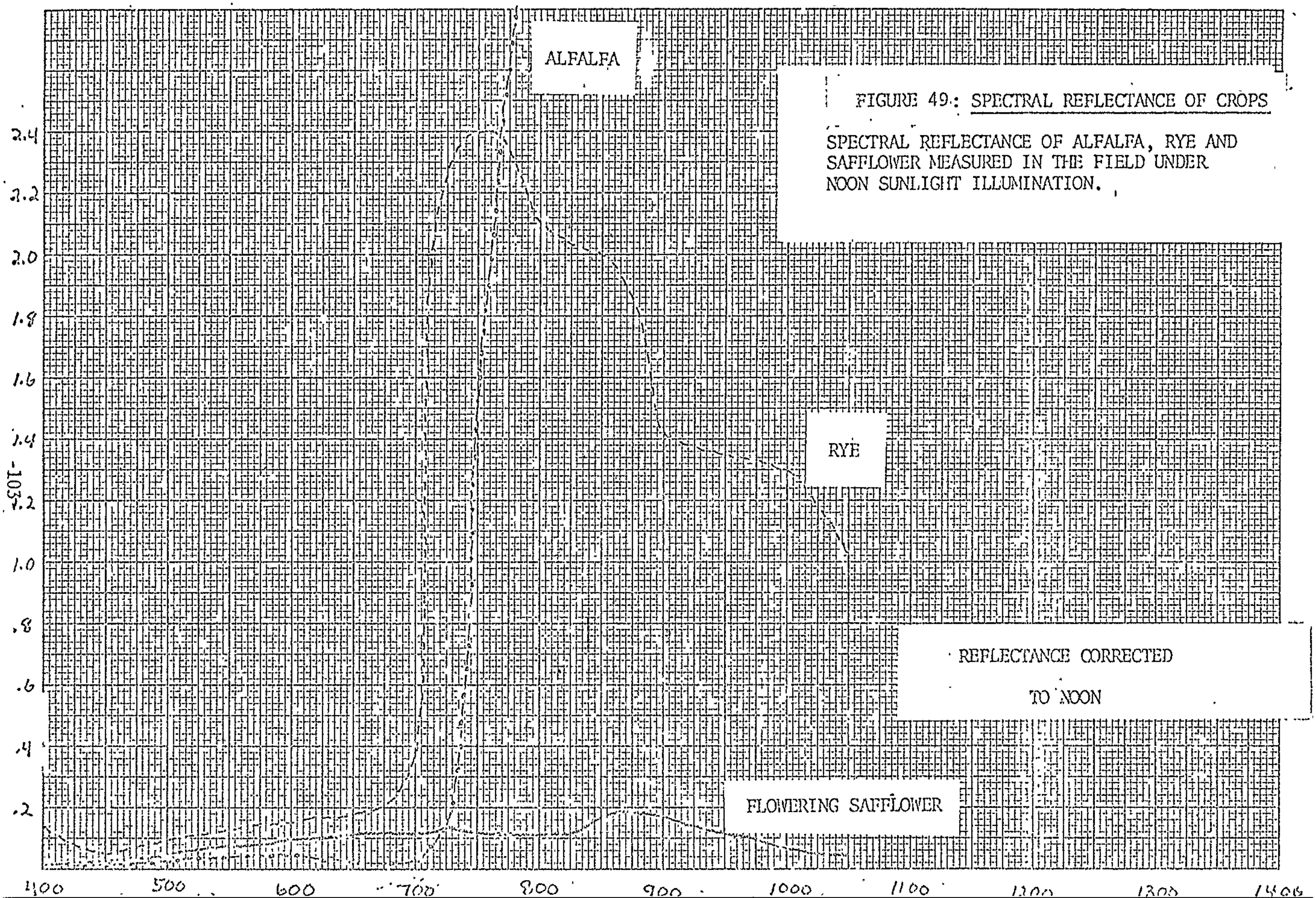


FIGURE 49: SPECTRAL REFLECTANCE OF CROPS

SPECTRAL REFLECTANCE OF ALFALFA, RYE AND SAFFLOWER MEASURED IN THE FIELD UNDER NOON SUNLIGHT ILLUMINATION.

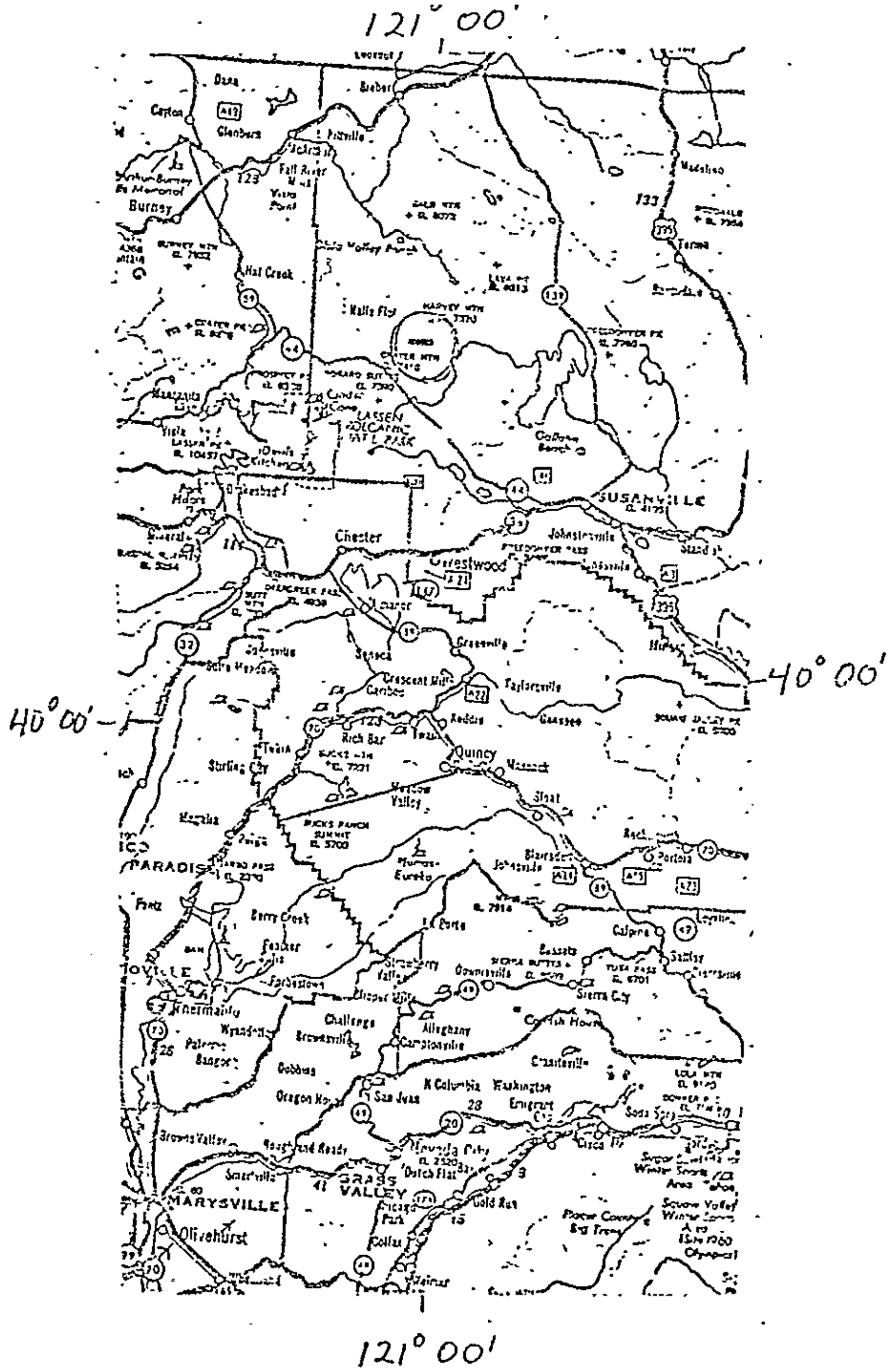


FIGURE 50

LOCATION OF THE NASA FORESTRY TEST SITES
AND APPROXIMATE FLIGHT LINES FLOWN.

wooded. The other area was relatively open range land located near Harvey Valley, California. The geographic locations of both these te sites as well as the approximate flight lines are shown in Figure 50.

Some significant results are shown in Figure 51. The top photo in this figure shows a wooded area adjacent to Silver Lake. The ground truth associated with this photograph, which was taken at 28,000 feet above sea-level (approximately 22,000 feet above mean terrain level), is shown in the top photo of Figure 52. The areas noted in the ground truth have been colorimetrically analyzed. These results are shown in Figure 53. Area A, indicated on the ground truth, is a stand of California Black Oak (Quercus Kelloggii). This stand, as can be seen from Figure 53, is clearly chromatically differentiated from area D, which consists of a stand of Riparian Hardwoods, mostly White Adler, and from area G which is a stand of Lodgepole Pine (Pinus Contorta). Also White Bir (area H) can be differentiated chromatically from areas containing Balck Oak and Lodgepole Pine.

The center photo in Figure 51 is the Harvey Valley Range area. The ground truth for which is shown in the center photo of Figure 52. Chromaticity measurements of the images shown on the ground truth are included in Figure 54. From this figure we see that Bromus Inermus grass, Big Sagebrush sites and dry rushes-sedge areas can be clearly differentiated on from the other. The colors of the images which relate to Low Sagebrush and Bromus Inermus grass can be less well chromatically separated

FIGURE 51-A
SILVER LAKE, CALIFORNIA AT 28,000 FEET ABOVE SEA LEVEL 7 AUGUST 1967. FALSE COLOR RENDITION--GREEN PROJECTED AS GREEN, RED PROJECTED AS BLUE, INFRARED PROJECTED AS RED.

FIGURE 51-B
HARVEY VALLEY AT 28,000 FEET ABOVE SEA LEVEL 7 AUGUST 1967 FALSE COLOR RENDITION--GREEN PROJECTED AS BLUE, RED PROJECTED AS RED, INFRARED PROJECTED AS GREEN.

FIGURE 51-C
SERPENTINE AREA AT 28,000 FEET ABOVE SEA LEVEL 7 AUGUST 1967 FALSE COLOR RENDITION--GREEN PROJECTED AS GREEN, RED PROJECTED AS BLUE, INFRARED PROJECTED AS RED.

FIGURE 51:

THREE FALSE COLOR RENDITIONS OF VARIOUS AREAS IN FORESTRY TEST SITE.

FIGURE 52-A

LEGEND- SILVER LAKE

A-QUERCUS KELLOGGII(CALIFORNIA BLACK OA
B-GLACIAL MORAINE(GRANITIC)WITH SPARSE COVERING OF MANZANITA BRUSH.
C-DRY MEADOW OF SEDGES AND GRASSES
D-RIPARIAN HARDWOODS(WHITE ALDER)
E-GRANITIC OUTCROP
G-PINUS CONTORTA(LODGEPOLE PINE)
H-ABIES CONCOLOR(WHITE FIR)

FIGURE 52-B

LEGEND- HARVEY VALLEY RANGE

1-INTEGRATION OF STANDING WATER IN AND AMONG,A DENSE STAND OF SEDGES(CAREX SP
2-PARTIALLY DRIED RUSHES AND SEDGES.
3-LOW SAGEBRUSH TYPE
4-BROMUS INERMUS GRASS
5-VERY DENSE, LUSH MEADOW VEGETATION DOMINANT SPECIES INCLUDE SEDGES, FORBS AND SOME WATER-LOVING GRASSES.
6-BIG SAGEBRUSH SITES
7-PONDEROSA PINE
8-MANZANITA BRUSHFIELD

FIGURE 52-C

LEGEND-SERPENTINE AREA

A-DUBAKELLA SOIL. GROUND COVER IS CEANOTHUS CUNEATUS(BACKBRUSH)
B-RIPARIAN HARDWOOD VEGETATION PRE-DOMINANTLY SALIX SP.(WILLOW)
C-MEADOW OF DRY GRASS WITH SOME SCAT-TERED SALIX SP.
D-MEADOW WITH A HIGHER PROPORTION OF VEGETATION
E-VERY MOIST MEADOW AREA
F-DENSE STAND OF MIXED CONIFERS ON CO-HASSETT SOIL
G-WET MEADOW, LUSH GRASSES AND SEDGES (CAREX SP.)
H-FAIRLY DENSE STAND OF TIMBER ON DUBA-KELLA SOIL.
I-BARE GRAVEL--GOLD DREDGE TAILINGS FROM EARLY MINING OPERATIONS.

FIGURE 52:

GROUND TRUTH FOR FORESTRY TEST SITES.

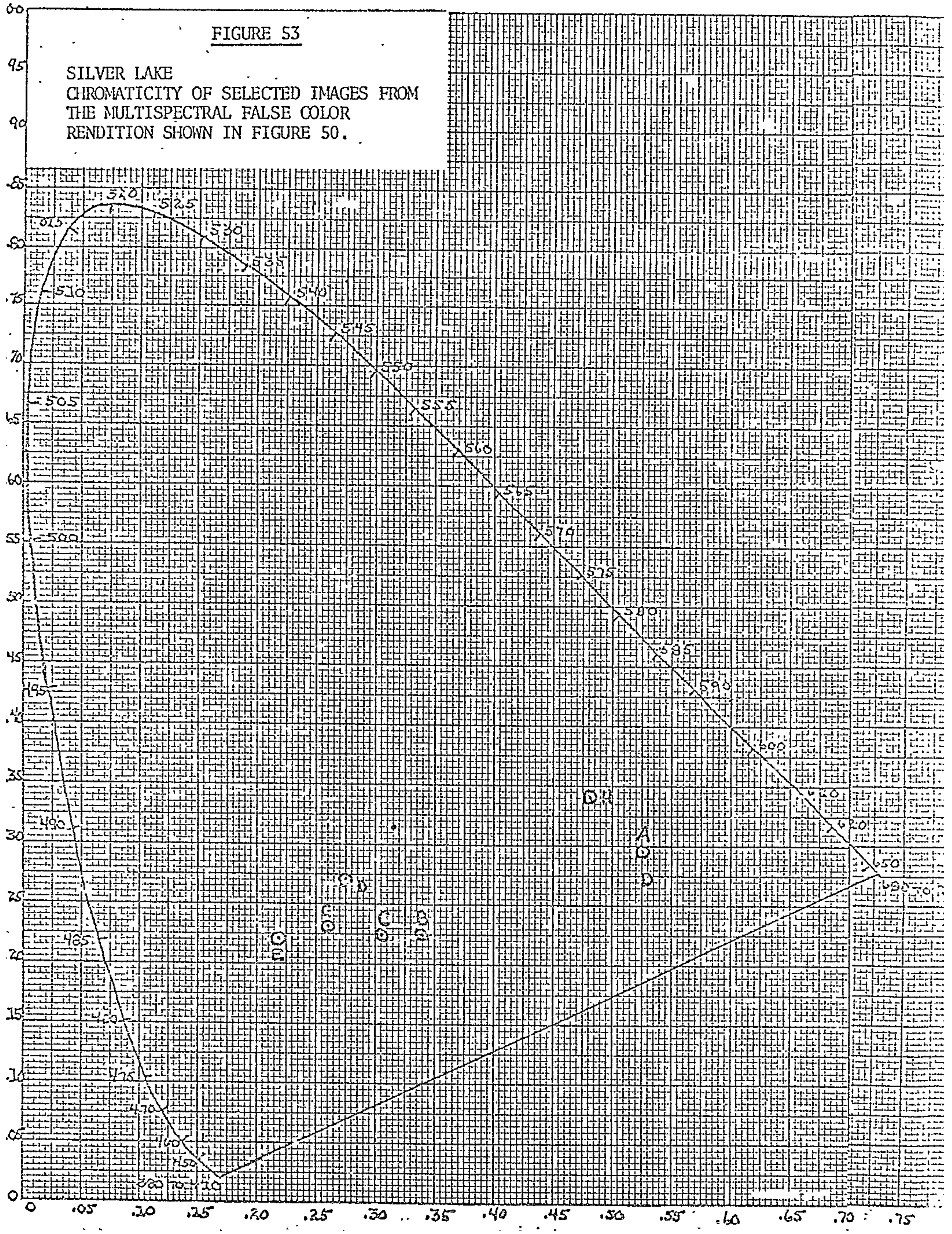


FIGURE 53

SILVER LAKE
CHROMATICITY OF SELECTED IMAGES FROM
THE MULTISPECTRAL FALSE COLOR
RENDITION SHOWN IN FIGURE 50.

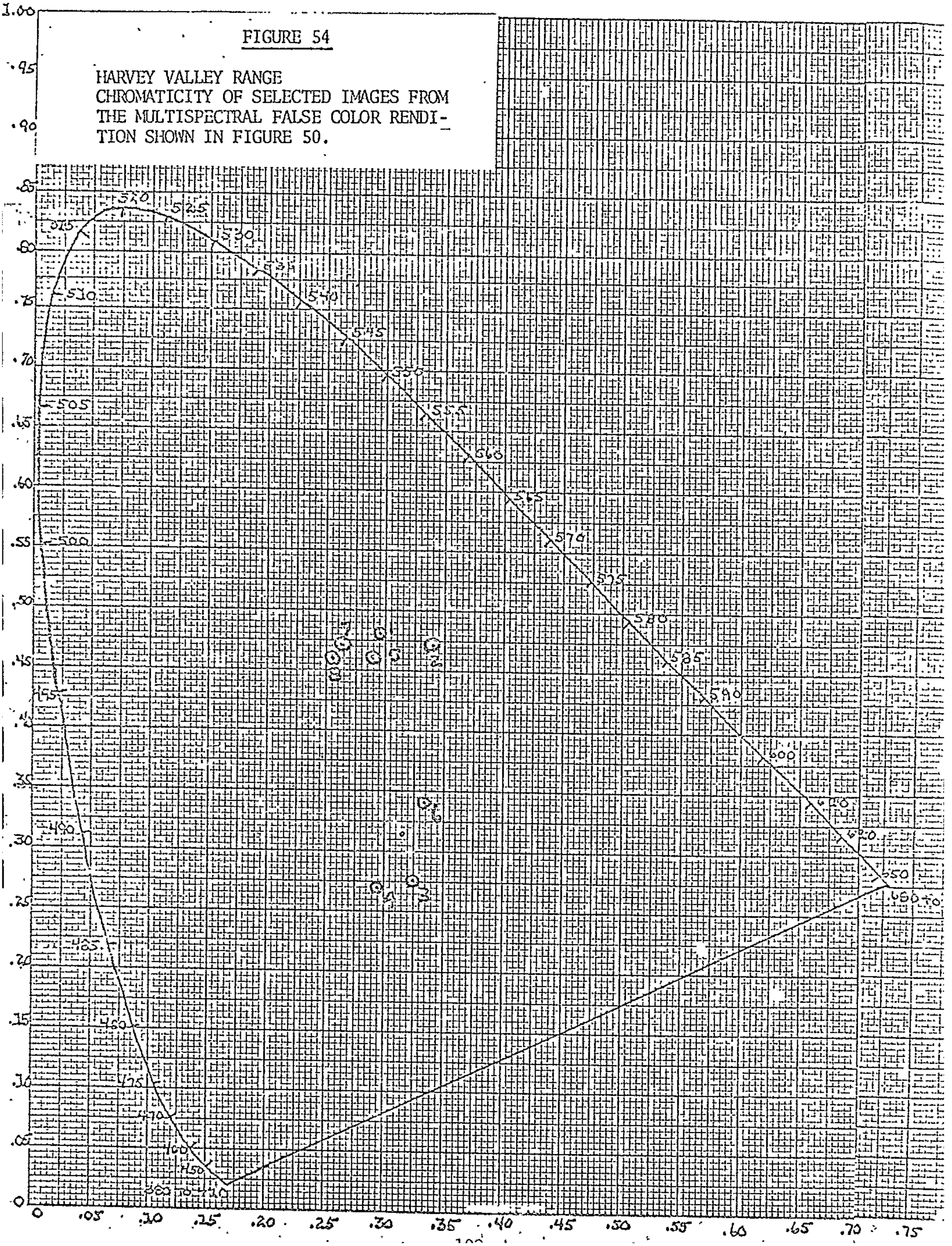
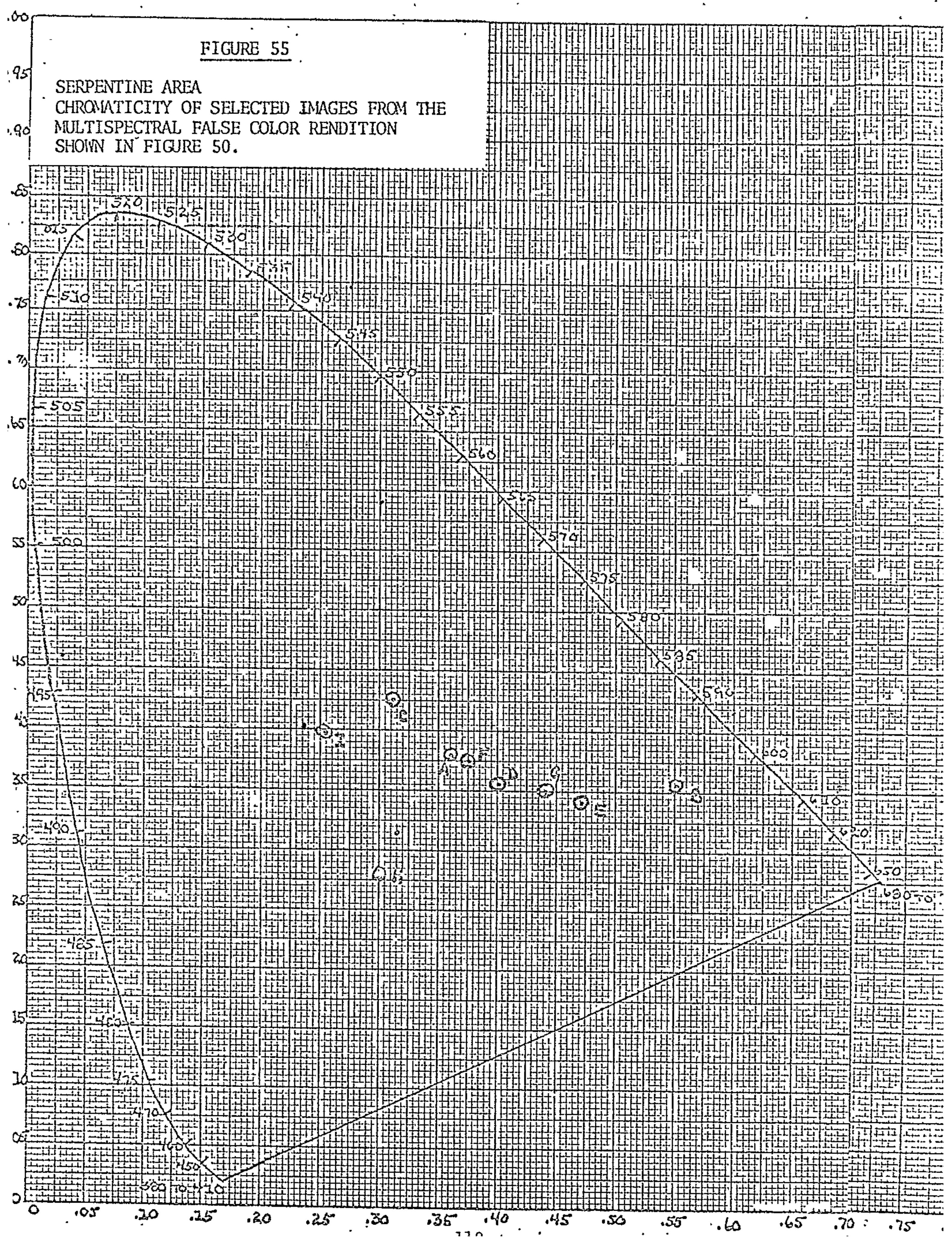


FIGURE 54

HARVEY VALLEY RANGE
CHROMATICITY OF SELECTED IMAGES FROM THE MULTISPECTRAL FALSE COLOR RENDITION SHOWN IN FIGURE 50.

FIGURE 55

SERPENTINE AREA
CHROMATICITY OF SELECTED IMAGES FROM THE
MULTISPECTRAL FALSE COLOR RENDITION
SHOWN IN FIGURE 50.



as is the case with stands of Ponderosa Pine and Manzanita brush embedded in the pine field.

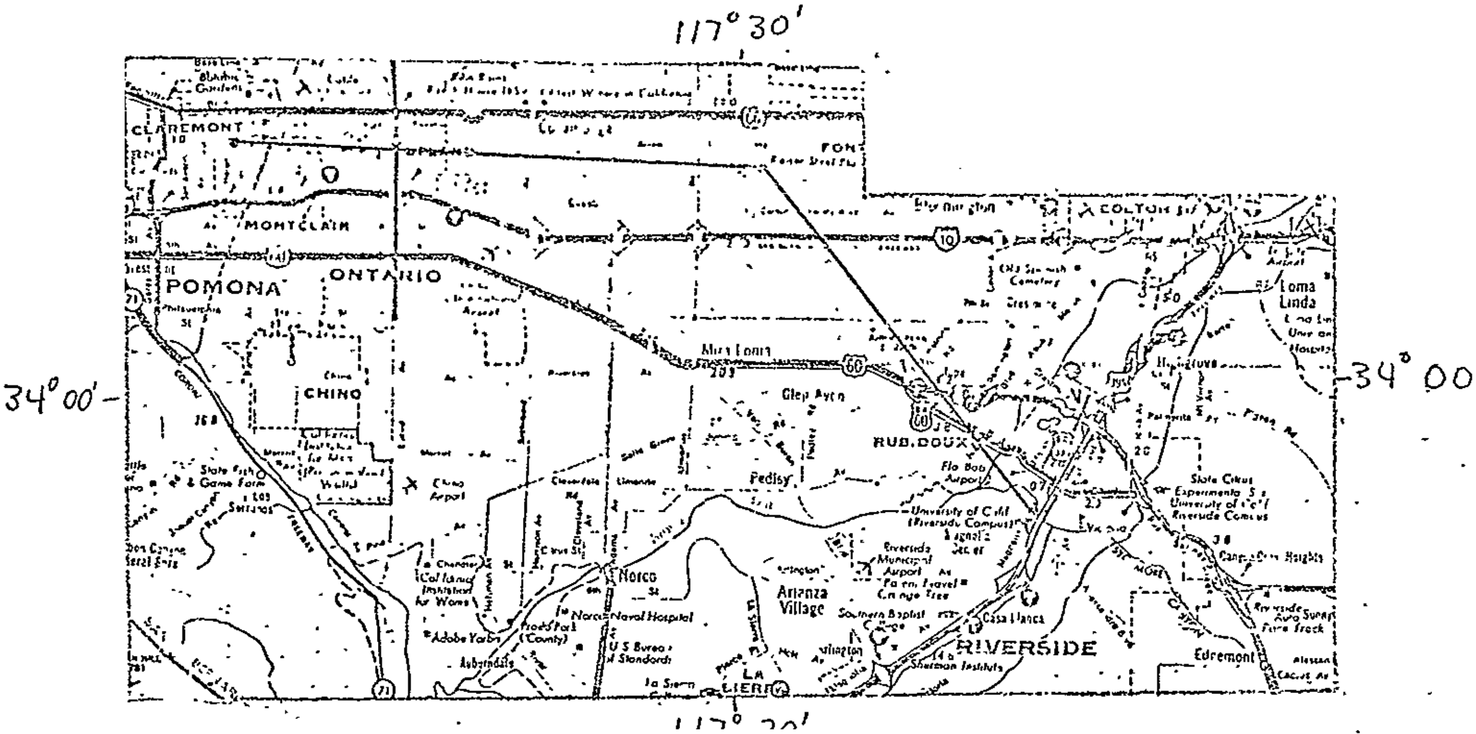
The bottom photo in Figure 51 is the Serpentine area of the Bucks Lake test site. In this rendition it has been possible to clearly differentiate all the items delineated in the ground truth shown in Figure 52. The chromaticity measurements of these images are shown in Figure 55. This additive color rendition is particularly significant because several independent measurements of images associated with areas identified as similar by the ground truth resulted in establishing identical color coordinates.

5.3 Geography

The Los Angeles Basin from Santa Monica to Riverside served as the geography-meteorology test site as shown in Figure 56. This area was over-flown on 3 and 4 August 1967 under widely different atmospheric conditions. The coastal area was visually clear while the inland Riverside area contained heavy smog accompanied by a then cirrus overcast at 20,000 feet.

Two different experiments were performed at this site:

1- Overflights of the areas were made at 15,000 and 28,000 feet for the purpose of comparing multiband color photography with subtractive color films (Aero-Ektachrome and Aero-Ektac



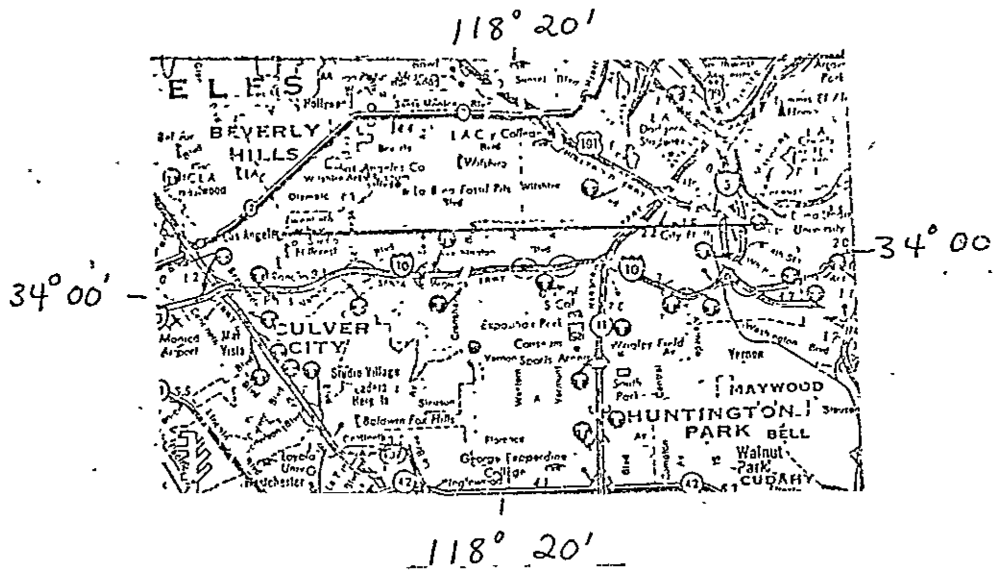


FIGURE 56

FLIGHT LINE COVERAGE OF THE NASA GEOGRAPHY TEST SITE AT LOS ANGELES chrome Infrared).

2-A series of photographs at incremental altitudes from 1,500 to 28,000 feet for the purpose of comparing the color fidelity of both multiband color and color films as a function of altitude.

The second experiment provided an opportunity for detailed quantitative analysis of the effects of apparently relatively clear atmosphere on both the multispectral color and Ektachrome color films.

Figure 57 shows the Ektachrome natural color photographs of target panels located on the ground at Century City (West Los Angeles) taken at altitudes of 1500,3000, 5000, 10,000,15,000, 28,000 feet. Figure 58 shows the chromaticity of the four colored panels measured on the Ektachrome photography at these altitudes. It can be seen from this figure that there exists considerable ambiguity between the blue and green targets as a function of altitude. However, both the red and yellow targets are well differentiated. The dominant wavelength of the red target is 600 nanometers, the dominant wavelength of the yellow target, 573 nanometers, with all targets being contained between 570 and 576 nanometers. We can see that the saturation of the colors of these two targets is relatively constant. The green target dominant wavelength varies from 505 to 555 nanometers accompanied by a great variability in saturation. More serious from a precision photographic standpoint is the color overlap between the blue and green targets as

FIGURE 57:

AERIAL EKTACHROME PHOTOGRAPHS AT THE INDICATED ALTITUDES ON 3 AUGUST 1967.

FIGURE 57-A
1500 FEET

FIGURE 57-B
3000 FEET

FIGURE 57-C
[illegible]

FIGURE 57-D
10,000 FEET

FIGURE 57-E
15,000 FEET

FIGURE 57-F
28,000 FEET

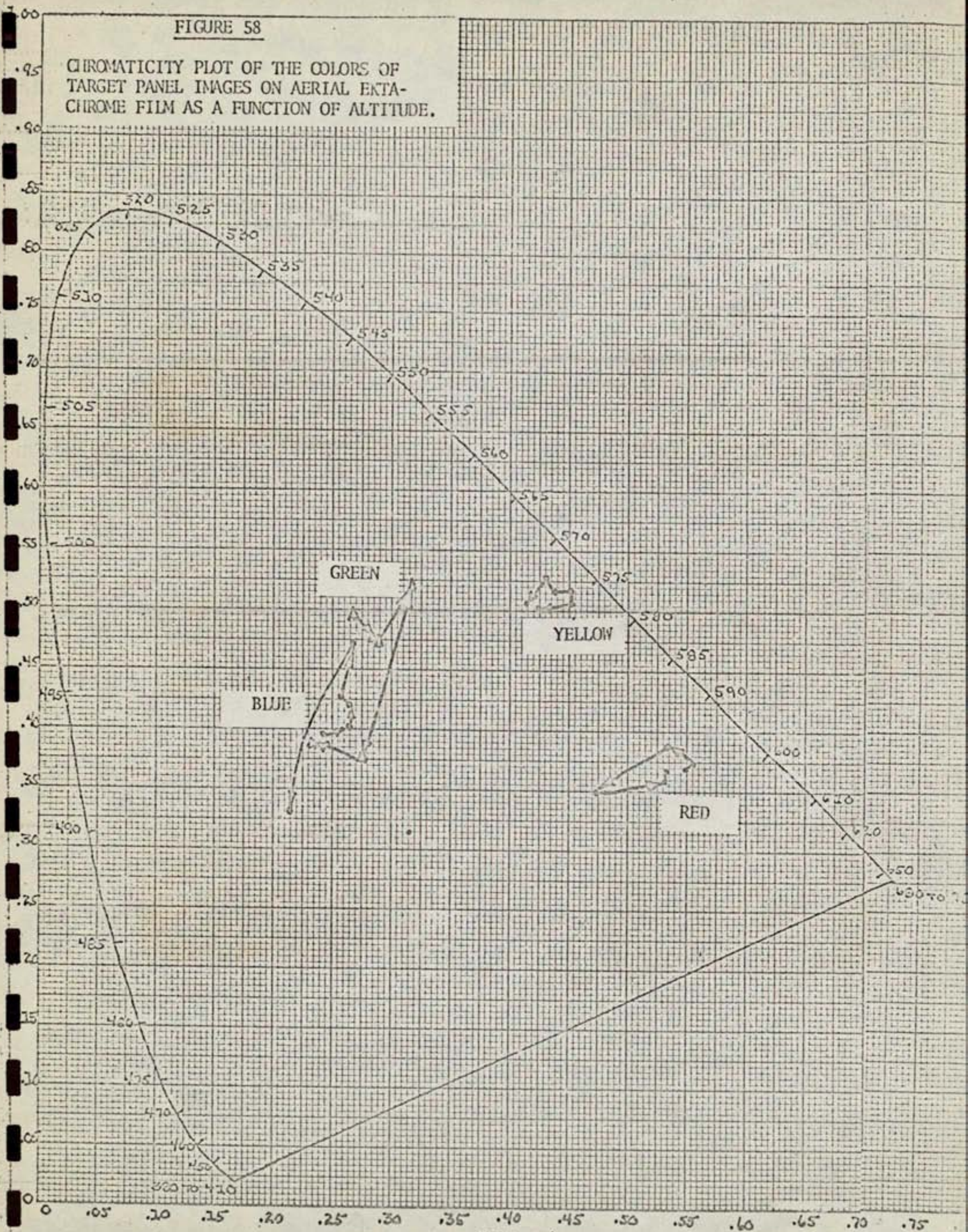


FIGURE 58

CHROMATICITY PLOT OF THE COLORS OF TARGET PANEL IMAGES ON AERIAL EKTACHROME FILM AS A FUNCTION OF ALTITUDE.

a function of altitude. Blue colors are mistaken for green as altitude varies, as can be seen from Figure 58.

Figure 59 presents a multispectral true color rendition of the same scene that was shown in Figure 59. Colorimeter measurements were made of the images of the color targets when the interpreter used the additive color viewer to provide what he considered to be the most natural reproduction of ground color. These results are shown in the Figure 60. This figure is again a chromaticity plot of the color measurements of the red, green, yellow and blue targets for an average of three observers who have attempted to match the scenes at the various altitudes to give what appeared to them to be a natural color rendition. Examination of this diagram shows the existance of considerable variability in the measured color of target panel images, however, the overlap between colors which existed on the color film is not present.

Figure 61 gives a most interesting comparison of the color of the targets as measured by a colorimeter on the ground (at the time the photography was taken) with the chromaticity of the additive color image when the color space generated by the viewer was manipulated to give the best color match to all four target panels in a single additive color presentation. It can be seen that the chromaticity of the red, green, white targets and their images are practically superimposed. The color of the yellow image is quite close to the color of the target and even the blue image, which is practically impossible to exactly

FIGURE 59:

MULTISPECTRAL TRUE COLOR PHOTOGRAPHS
OF THE TARGET PANELS AS A FUNCTION OF
INCREASING ALTITUDE

FIGURE 59-A
1500 FEET

FIGURE 59-B
3000 FEET

FIGURE 59-C
5000 FEET

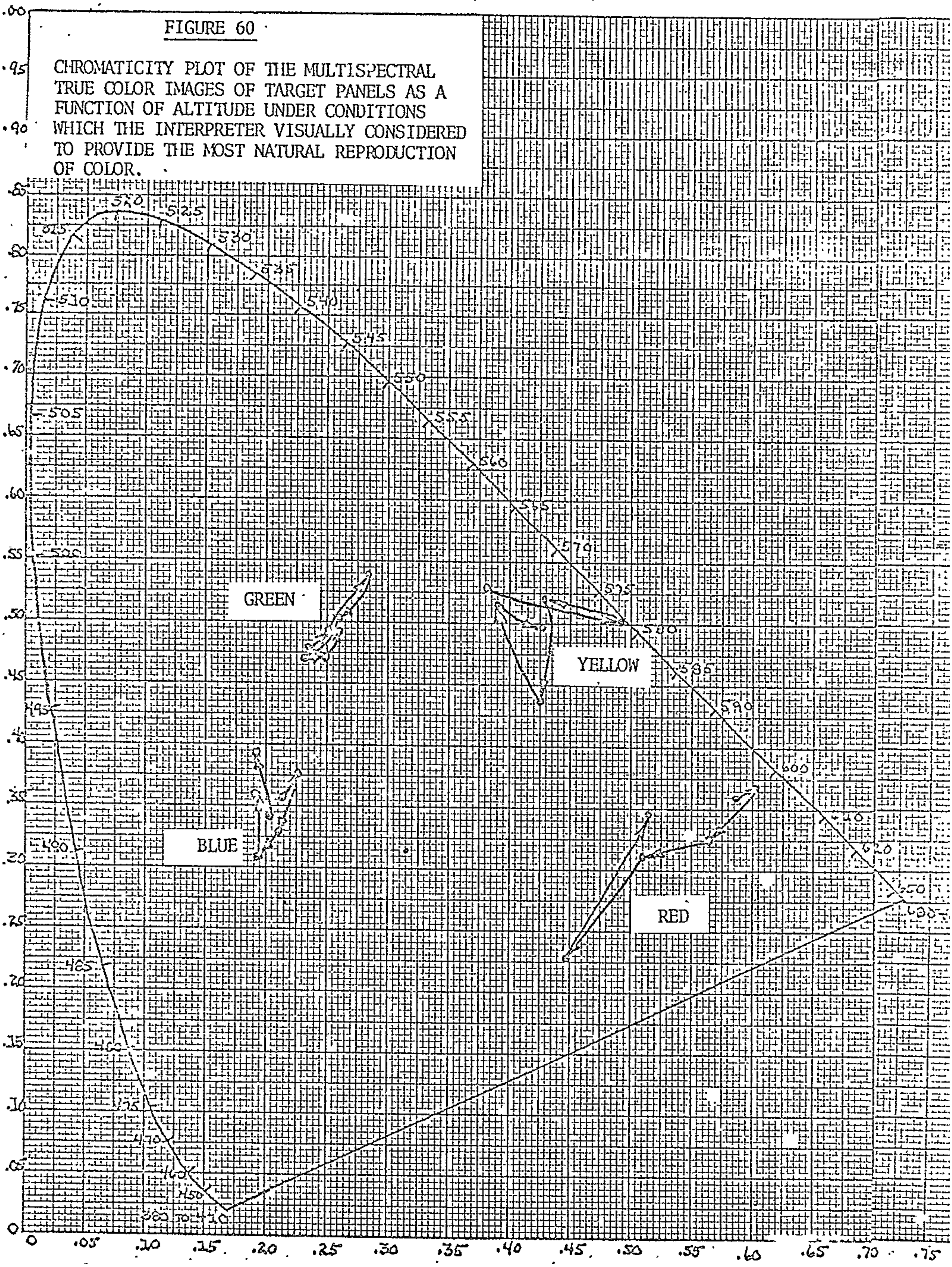
FIGURE 59-D

FIGURE 59-E
15,000 FEET

FIGURE 59-F
28,000 FEET

FIGURE 60

CHROMATICITY PLOT OF THE MULTISPECTRAL TRUE COLOR IMAGES OF TARGET PANELS AS A FUNCTION OF ALTITUDE UNDER CONDITIONS WHICH THE INTERPRETER VISUALLY CONSIDERED TO PROVIDE THE MOST NATURAL REPRODUCTION OF COLOR.



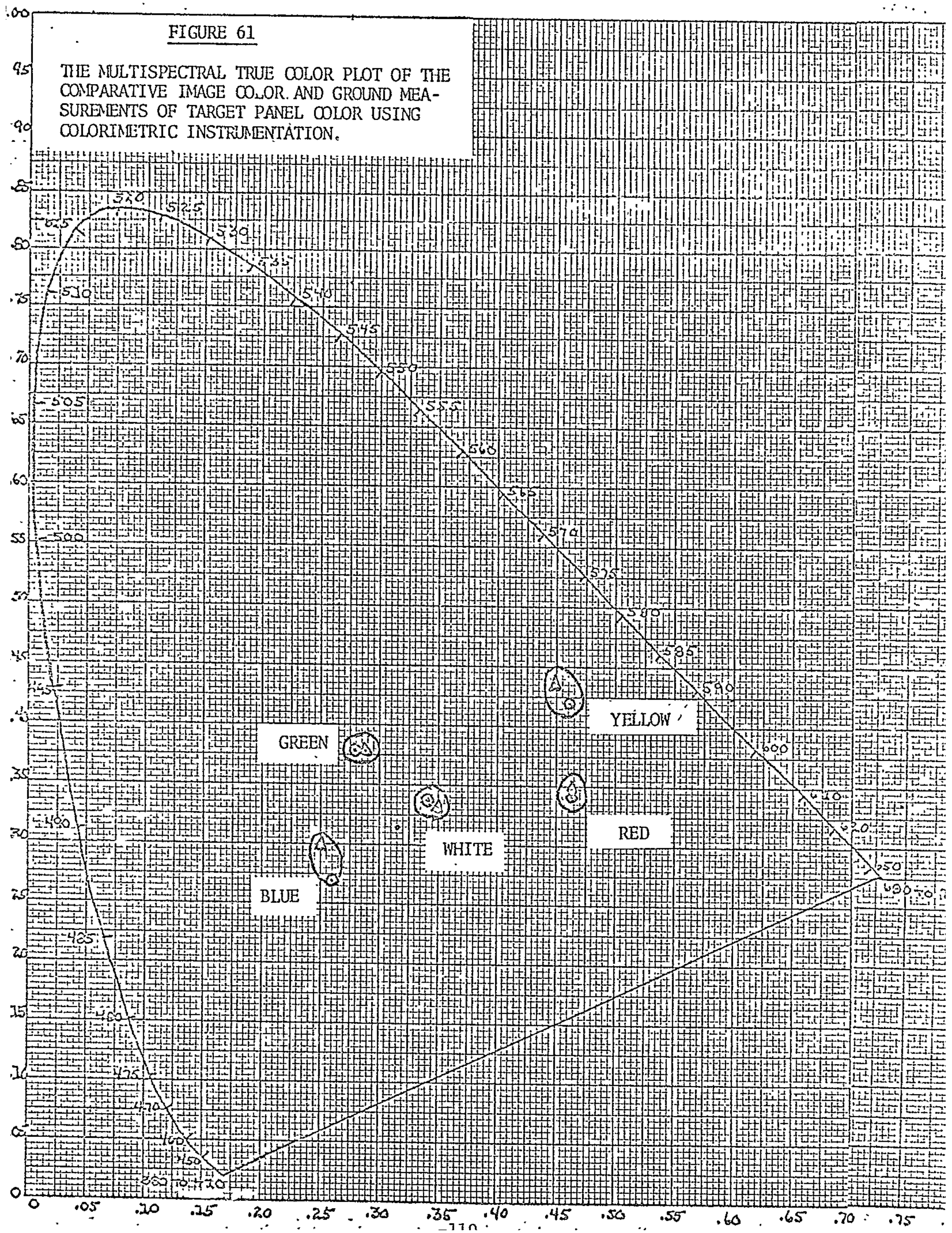


FIGURE 61

THE MULTISPECTRAL TRUE COLOR PLOT OF THE COMPARATIVE IMAGE COLOR AND GROUND MEASUREMENTS OF TARGET PANEL COLOR USING COLORIMETRIC INSTRUMENTATION.

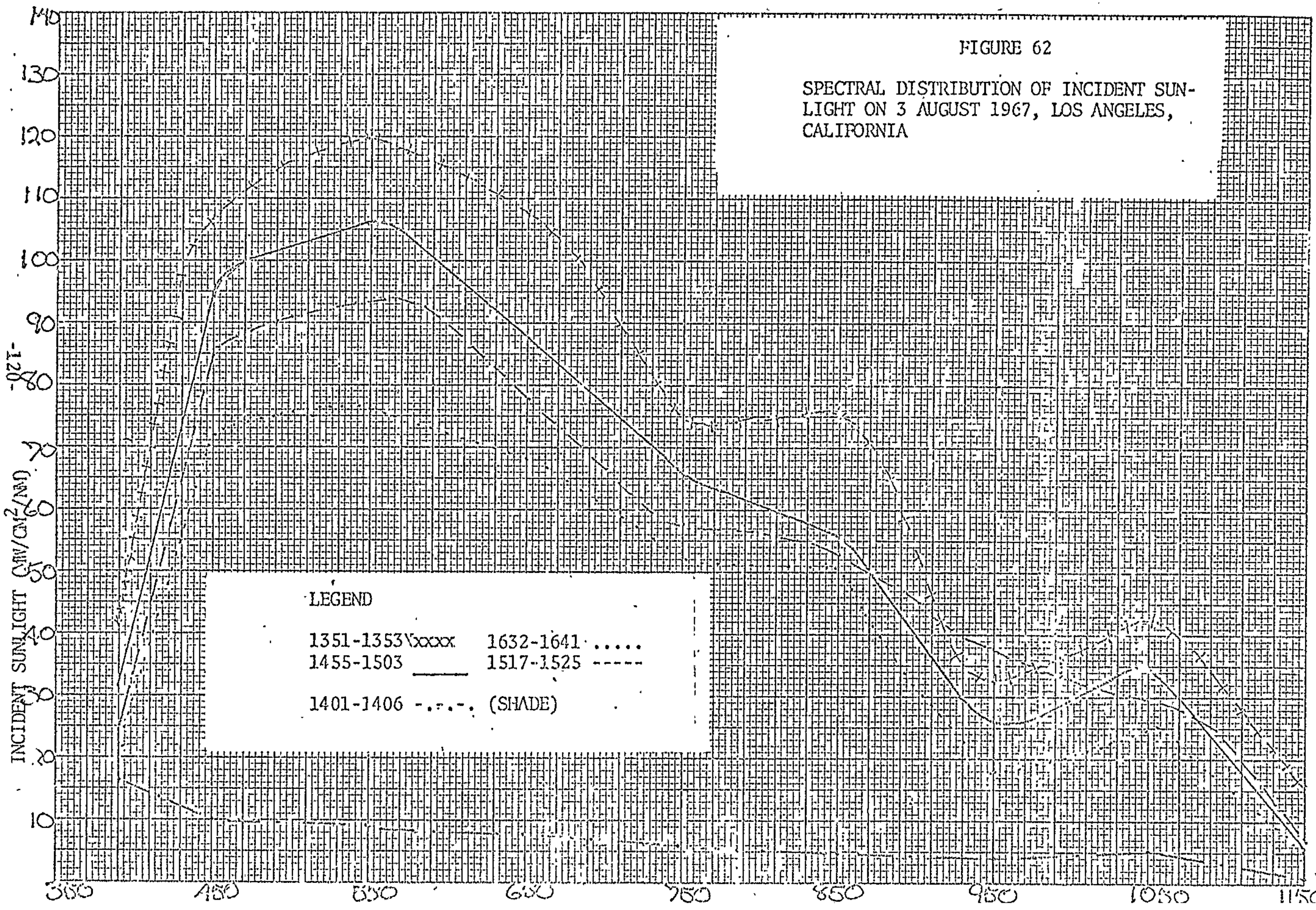


FIGURE 62

SPECTRAL DISTRIBUTION OF INCIDENT SUNLIGHT ON 3 AUGUST 1967, LOS ANGELES, CALIFORNIA match in any color scheme, is [illegible] the measured ground color. The spectral distribution of sunlight during the period in which the photography was taken is shown in Figure 62.

5.4 Geology

Two geology test areas were overflown during the experiment. The one receiving the primary emphasis was the White Mountain area north of Bishop, California. The other area was Mono Craters. Both these areas are shown in Figure 63.

Figure 64 is a multispectral false color reproduction of an area of the Owens Desert, north of Bishop, California, identified as Bishop Tuff. Photography was taken at 24,000 feet altitude above the terrain on 6 August 1967. The area of the Bishop Tuff has been extensively analyzed and geological maps have been prepared by Dwight Crowder of the U.S. Geological Survey. Information from these maps has been overlaid on the photography as shown in Figure 64.

The area consists of three predominant features, non-welded tuff, partially welded tuff, alluvium. The multispectral color rendition shown has been obtained by projecting the green band as green, the red band as blue and the infrared band as red.

The chromaticity diagram in Figure 65 shows the plot of four color measurements made from the viewer screen in each of the identified areas.

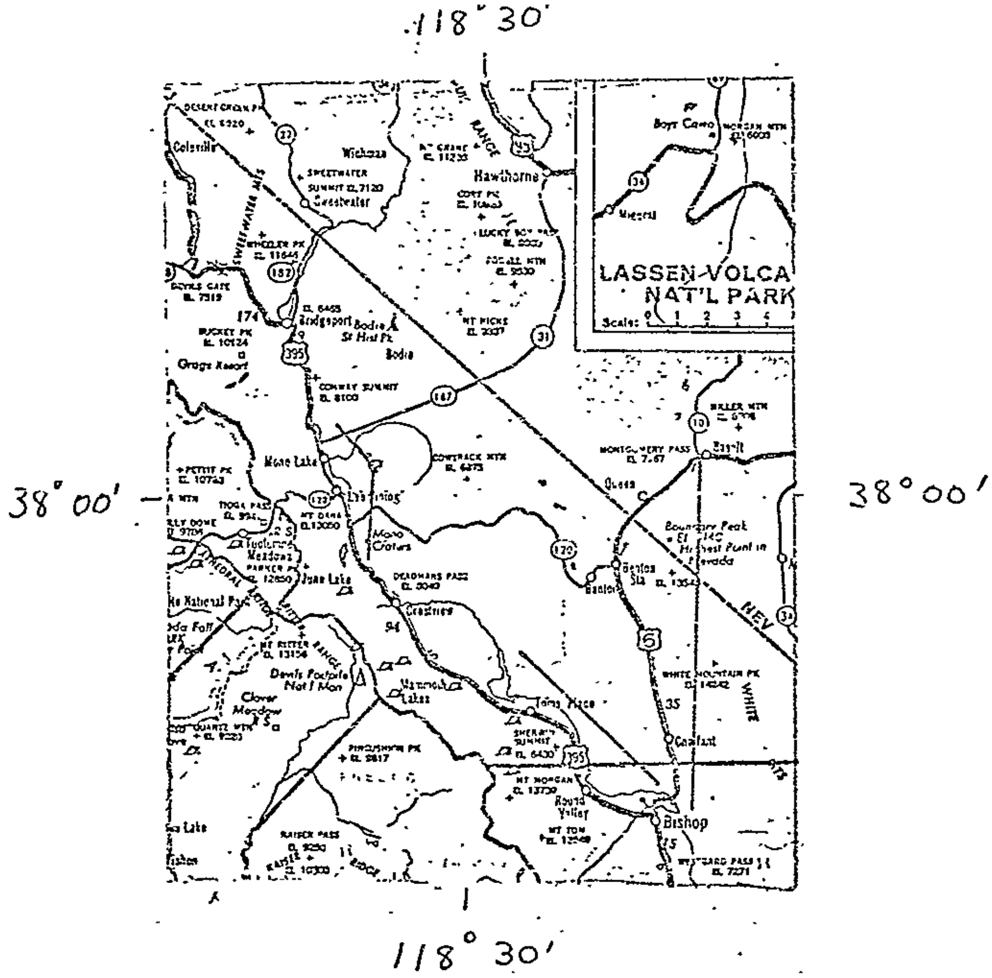


FIGURE 63

WHITE MOUNTAIN AREA AND MONO LAKE GEOLOGY TEST SITE SHOWING FLIGHT LINES FLOWN ON 4, 5 AND 6 AUGUST 1967.

LEGEND

PW- PARTIALLY WELDED TUFF
QAL- ALLUVIUM
NW- NON-WELDED TUFF
Kgr-GRANITE BASEMENT

FIGURE 64:

MULTISPECTRAL COLOR PHOTOGRAPHY
OF BISHOP TUFF AREA OF THE OWENS
DESERT WITH GEOLOGICAL ANNOTATIONS

From this data we see that partially welded tuff image possesses a dominant wavelength of approximately 498 nanometers differentiated in saturation from alluvium and the granite basement areas. The latter two areas have the same dominant wavelength as partially welded tuff but are more saturated in color. Measurements show that the chromaticity of the image area identified as granite basement is completely contained in the alluvium image. This would indicate that the chromaticity of the image would not allow the photo-interpreter to differentiate these two geological conditions but that he would have to rely on other features of theimage such as texture. Non-welded tuff exhibits a dominant wavelength of 489 nanometers and is chromatically completely separate from the other three images. Most of the measurements shown fell within the areas on the chromaticity diagram noted. However, it was possible to find anomolous areas within each category which would lie in other categories. For instance, it was possible to find an image in partially welded tuff that would fall in non-welded tuff chromaticity coordinates. This indicates that chromaticity analysis of geological features might have most fruitful results on a statistical colorimetric analysis by areas.

Figure 66 also shows an area in the Owens Desert in the Bishop Tuff region. The multispectral photography was obtained at 24,000 feet above sea-level on 6 July 1967. The image was obtained by projecting the green band as green, the red band as blue and the infrared as red. The anno-

LEGEND

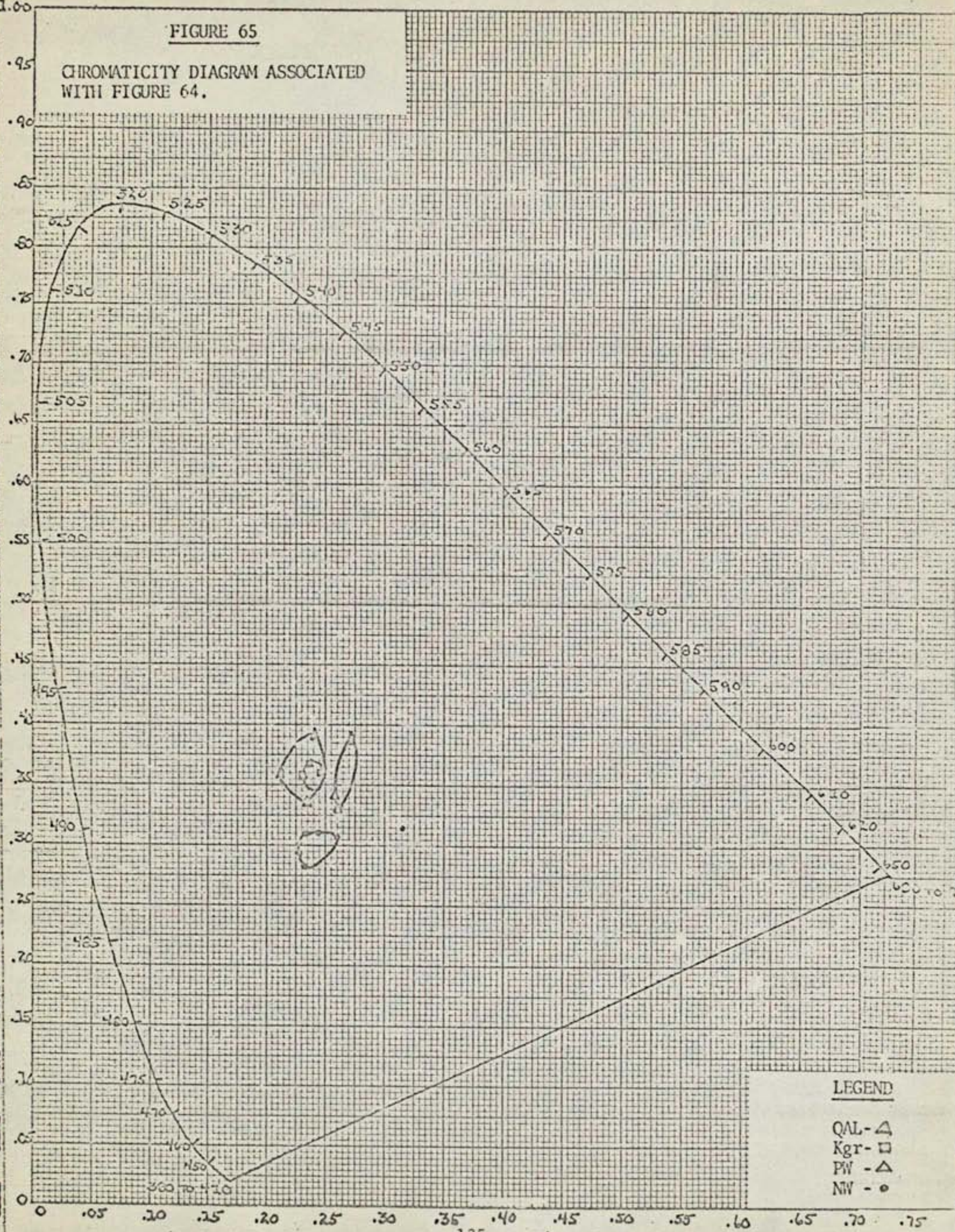
QAL- ALLUVIUM
NW - NON-WELDED TUFF
PW - PARTIALLY WELDED TUFF
QFP- FLOOD PLAIN DEPOSITS

FIGURE 66:

MULTISPECTRAL COLOR PHOTOGRAPHY OF BISHOP TUFF AREA NORTH OF BISHOP, CALIFORNIA WITH GEOLOGICAL ANNOTATIONS.

FIGURE 65

CHROMATICITY DIAGRAM ASSOCIATED WITH FIGURE 64.



tations from the geological map of the area constructed during the period in which the photography was taken is shown as an overlay on the photograph. The five significant features, alluvium, flood plane deposits, non-welded tuff, partially welded tuff and tuff altered by vapor phase crystallization are shown on the overlay.

The chromaticity plot of the colorimetric measurements obtained from the viewer screen are shown if Figure 67. Perhaps the most striking feature of this figure is the large variation exhibited by flood plain deposits. The colorimetric measurements obtained from this image area show great diversity. This is undoubtedly due to the fact that large amounts of vegetation which appears as red and standing water bodies appearing as cyan, are shown in this area. Partially welded tuff in this renditon exhibited a dominant wavelength of 498 nanometers similar to Figure 64. However, measurements showed that non-welded tuff and tuff altered by vapor phase crystallization occupied the same chromaticity coordinates as the partially welded tuff. Alluvium, on the other hand, appeared separate chromatically from the other image areas.

Figure 68 shows a multispectral rendition of the White Mountain area east of Bishop, California. As in the previous two images shown, the annotations have been provided by geological investigation covering the time the photography was taken. There are three predominant features shown, sedimentary deposits, volcanic deposits, gravel and sand with the existance of two pronounced fault lines.

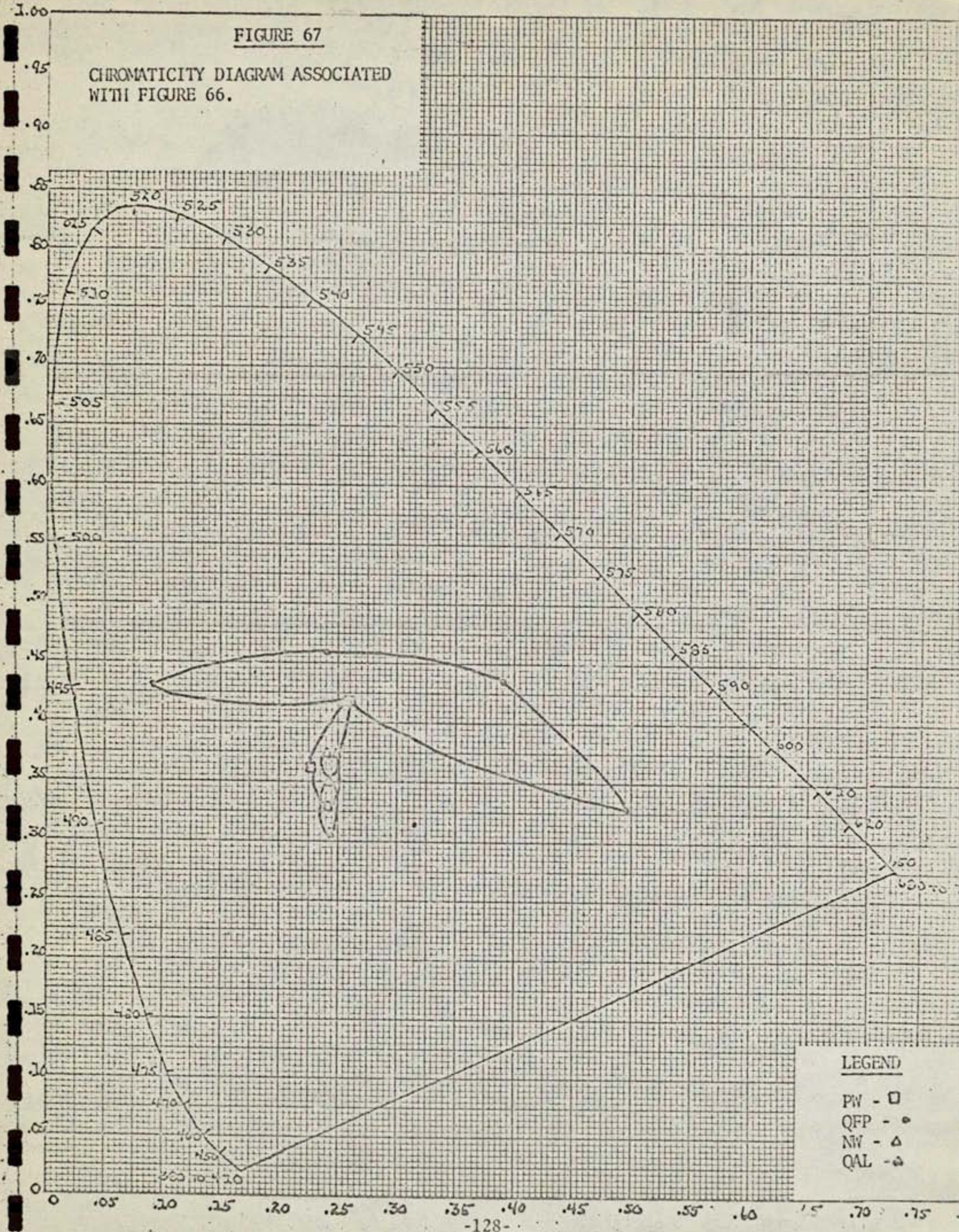


FIGURE 67

CHROMATICITY DIAGRAM ASSOCIATED WITH FIGURE 66.

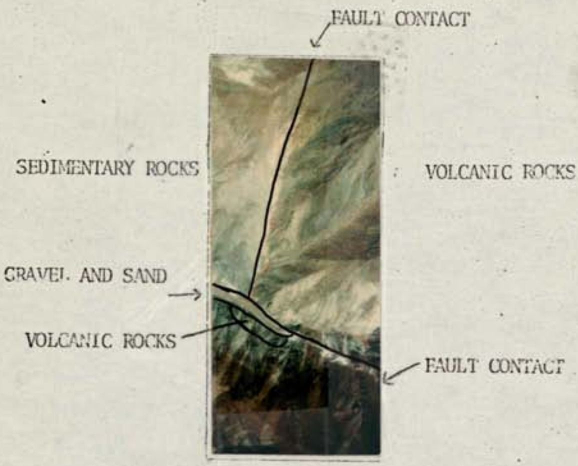


FIGURE 68:

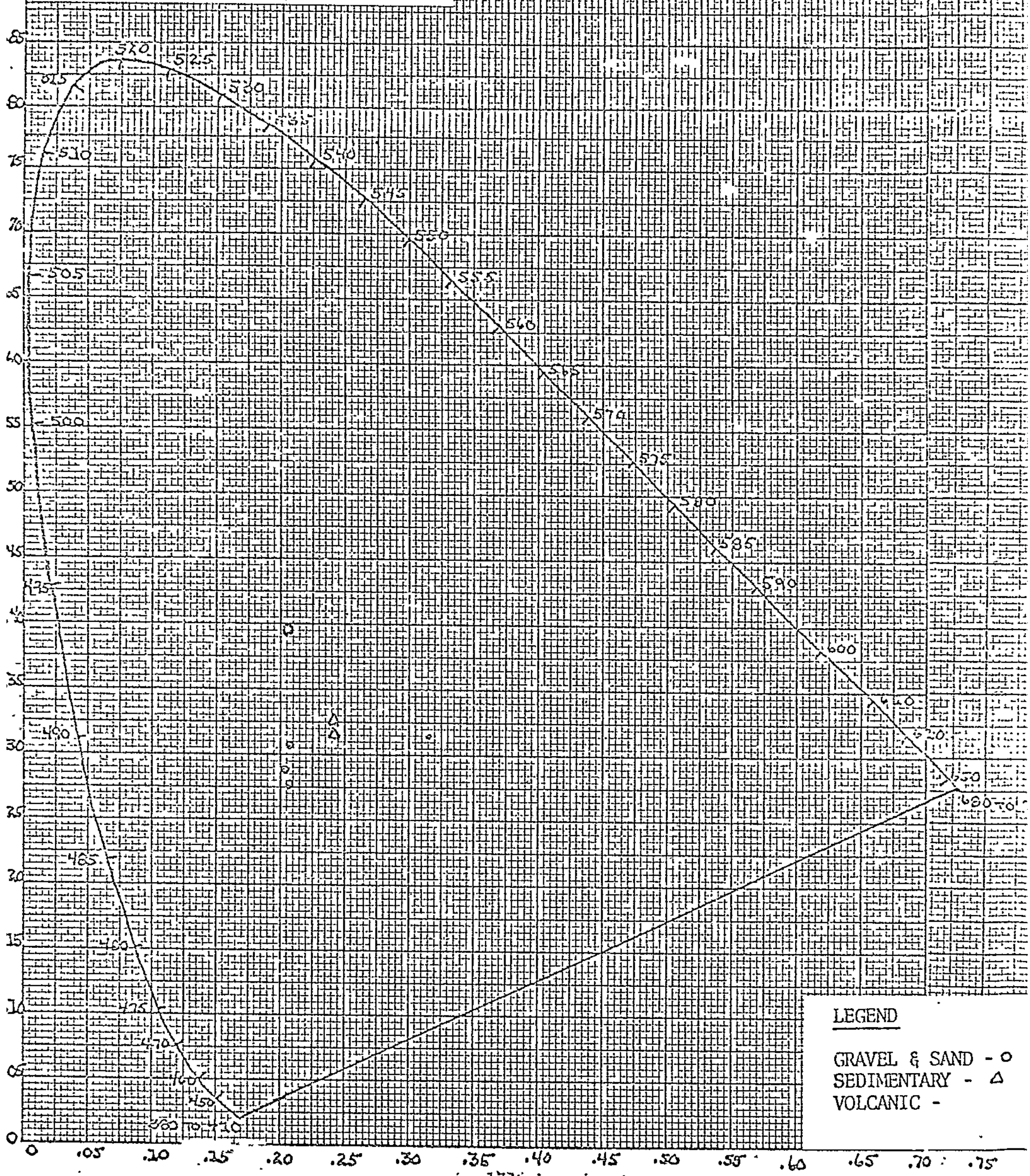
MULTISPECTRAL COLOR PHOTOGRAPHY
OF WHITE MOUNTAIN AREA WITH
GEOLOGICAL ANNOTATIONS

The multispectral rendition has been obtained by projecting the green band as green, the red band as blue, and the infrared band as red. Numerous measurements of the chromaticity of the projected image in the areas indicated are shown in Figure 69. Here we see that the chromaticity of the images in the three areas is distinct both in dominant wavelength and saturation.

The color of the same images taken from an Ektachrome infrared photograph of the same area which was obtained at identically the same time as the multispectral photo is shown in Figure 70. From the plot of the image color shown in this figure, we see that less chromatic separation of the images has been achieved on the subtractive color films in this particular photographic situation.

FIGURE 69

CHROMATICITY DIAGRAM ASSOCIATED WITH FIGURE 68.



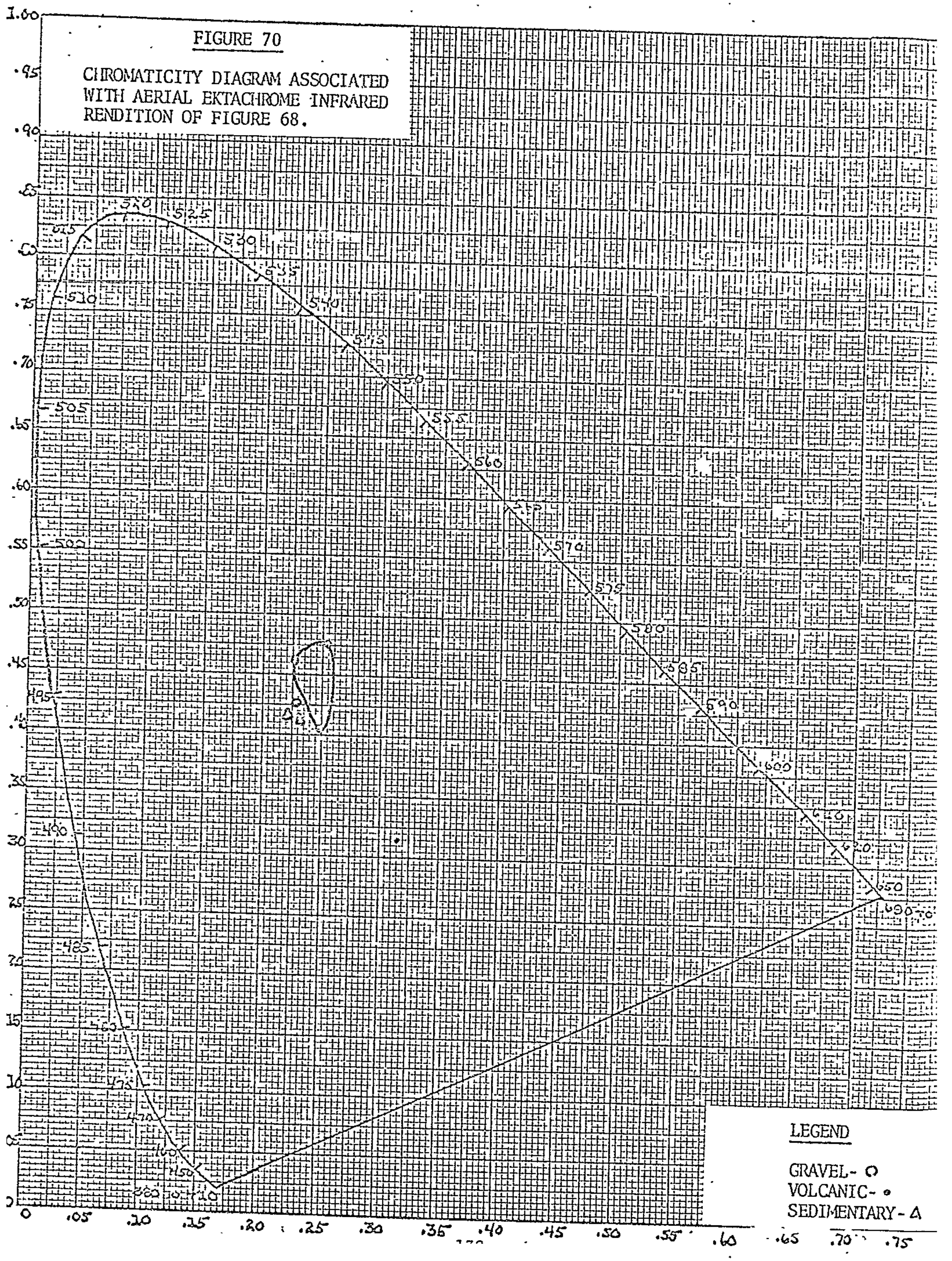


FIGURE 70
CHROMATICITY DIAGRAM ASSOCIATED WITH AERIAL EKTACHROME INFRARED RENDITION OF FIGURE 68.
LEGEND
GRAVEL- O
VOLCANIC- •
SEDIMENTARY- Δ

SECTION 6

CONCLUSIONS

The experiment dicussed herein was designed to evaluate the utility of multiband color photography for earth resource applications. This was accomplished by using a multispectral system in which most of the known image forming errors had been minimized. The choice of spectral bands used was limited by lack of definitive spectral data on environmental objects and was constrained to approximate the spectral sensitivity of color films.

Photography using conventional color films sensitive to the visible and infrared spectrum was simultaneously taken. Ground control was incorporated for the test site of each discipline which included: calibrated color and "grey scale" target panels, measurement of incident solar radiation, reflectance spectra measurements and colorimetric measurements.

Comparative colorimetric measurements of the resulting multispectral additive color imagery demonstrated the capability of this technique to compensate for both the variations in solar illumination and atmospheric effects that were encountered during the experiment. Using taking filters which approximated the wavelength sensitivity of the subtractive color films which were used, it was possible to establish spectral colorimetric signatures for certain classes of environmental phenomenon. Analysis of the test results showed: (1) chromatic image errors due to camera, processing and viewer tolerances can be decreased to a point where colorimetric analysis can be reliably performed; (2) variations in the intensity and spectral distribution of solar radiation can be eliminated, (3) the directional (non-lambertian) spectral reflectance characteristics of objects and the dynamic nature of on vivo reflectance spectra are critical residual environmental parameters, (4) spectral reflectance measurements of classes of environmental objects taken en vivo indicate that significant improvement in spectral color signatures could be expected using taking filters which subdivided the 650 to 800 nanometer band of the spectrum.

Comparative colorimetric analysis of the image produced by the multispectral system and the image produced by subtractive color films demonstrated that it was possible to: (a) produce an additive color rendition in which the image colors were very close to object color, (b) create a false color space in which environmental objects which visually appeared to have quite similar color characteristics on the ground were made to have decidedly dissimilar characteristics in the additive color image.

SECTION 7

ACKNOWLEDGEMEN

The investigation reported in this experiment was initiated by Donald Orr and Col. Alden Galvocoresses at NASA headquarters, Washington and was conducted under the technical cognizance of Leonard Nicholson, NASA Manned Spacecraft Center Houston, Texas.

The field phase of the experiment was conducted by Long Island University in conjunction with the School of Forestry, University of California, Berkeley. William Prss (LIU) supervised the ground measurements assisted by William Draeger (UC), Eric Janes (UC), John Thomas (UC), Larry Pettinger (UC), and Gene Thorley (UC). At the geography test site, assistance was provided by Dr. Leonard Bowden (UCR), Robert Alexander (ONR), Donald Orr USA (GIMRADA), and Jack Estes (UCLA). At the geology test site, Dwight Crowder (USGS) provided ground truth data.

Analysis of both additive color imagery and conventional color films was performed for each test site by the following:

Agriculture & Forestry:	Dr. Robert Colwell (UC), William Draeger (UC), Jerry Lent (UC).
Geography:	Dr. Leonard Bowden (UCR), Dr. Robert Pease (UCR),
Geology:	Dwight Crowder (USGS), Michael Sheridan (UA), Gary Ballew (SU).

Photo reproductions of the viewer screen were made by Robert Anderson(LIU)

Organizations abbreviated above are (alphabetically) as follows:

LIU- Long Island University

NASA- National Aeronautics and Space Administration

ONR- Office of Naval Research

SU- Stanford University

UA- University of Arizona

UC- University of California at Berkeley

UCLA- University of California at Los Angeles

UCR- University of California at Riverside

USA GIMRADA- U.S. ARMY, Geographic Intelligence Mapping Research and Development Agency.

USGS- United States Geological Survey.

SECTION 8

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APPENDIX A

GROUND SPECTRORADIOMETERS AND COLORIMETER INSTRUMENTATION

The accuracy and precision of the data presented on the (1) spectral distribution of incident solar radiation, (2) the spectral reflectance of ground objects, (3) color of target panels, is dependent on the instrumentation used.

Significant operating characteristics of the instrumentation and its calibration, where applicable, are discussed herein to present the technology used to make the measurements presented throughout this experiment.

Characteristics of the Instrumentation Used to Measure Incident Sunlight

A spectroradiometer using a wedge interference filter system enabling the spectrum from 380 to 1250 nanometers to be continuously scanned was used to determine the spectral distribution and intensity of the solar radiation incident upon the environment. The instrument was a modified version of the model SR Spectroradiometer manufactured by the Instrumentation Specialties Co., in which a James Chopper relay was placed in the coherent detector assembly to improve reliability. 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 important because the incident radiation falls upon the earth's surface and is reflected into the aerial camera lens regardless of its original direction of propagation. True cosine response also eliminates the need for precise aiming of the instrument.

Whereas a radiometer measures in units of energy rate intensity such as microwatts per centimeter square, a spectroradiometer 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 when spectral photography is taken since a graph of spectral distribution of radiant intensity versus wavelength can be obtained. The area under such a curve will be numerically and dimensionally equal to energy available in the wavelength interval of interest. The spectroradiometer used was 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 calibration of the spectroradiometer was verified using a regulated voltage calibration unit manufactured by Instrumentation Specialties Co. A spectral standard lamp, serially numbered and individually calibrated against the National Bureau of Standards was used. The lamp had an absolute accuracy of plus or minus five percent relative to the NBS standard. The precise regulation of the current to the lamp was maintained by a precision electrical power supply unit.

The half bandwidth of the spectroradiometer used to measure the incident illumination is approximately 15 millimicrons in the 380 to 750 range and 30 millimicrons in the 750 to 1250 range. Stray light response to unwanted wavelengths of 15 millimicrons bandwidth and far from the wavelength of interest is usually in the order of .01 percent. Stray light error results in 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 measurements of red rich light sources are made, such as solar radiation in the afternoon. The instrument reads approximately three percent too high at 400 millimicrons when measuring a standard 2854 degree Kelvin source because of stray light passage of longer wavelengths. This amount of error has been compensated by measuring the stray light alone, placing a blue absorbing filter over the sensing head and noting the amount of stray light indicating on the meter. This value has been subtracted from the measured intensity to determine the correct values.

The periodic calibration of the spectroradiometer used for measuring incident sunlight allowed an accuracy of plus or minus seven percent in the long wavelength of the spectrum and plus or minus ten percent in the short wavlength 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 wavelengths measured is approximately plus or minus three percent.

Characteristics of the Instrumentation Used to Make Reflectance Measurements

The reflectance spectroradiometer system assembled from components manufactured by EG &GGInc. and Bausch & Lomb was used to measure the average power of the solar radiation reflected by the target panels. By means of a grating monochromator, these energy and power readings can be made at a selected wavelength over a bandwidth determined by the grating and 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, 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. This reflectance spectroradiometer was used to measure the relative distribution of radiation reflected by the ground targets. A typical arrangement of the surface targets is shown in Figure 15 . These targets were oriented to minimize the secondary reflection from other surface objects (such as trees) incident upon them.

The reflectance spectroradiometer is designed so that light reflected from an object passes through a diffuse system and is directed by the collective lens into the monochromator housing via the entrance slit. Calibration accuracy is obtained when the light incident on the diffuser is imaged on the entrance slit, completely filling the slit area with light. A collective lens in the beam input optics in front of the monochromator entrance slit, collects the incident light which is properly matched with the diffuser to create a uniform illuminating bundle inside the monochromator housing. This bundle is them incident on a plane diffraction grating where it is angularly dispersed according to wavelength. Each wavelength present in the source bundle reflec off the diffraction grating at a different angle. The grating can be rotated to direct any selected wavelength bundle onto the center of a concave mirror. The mirror collects the light and, with the help of a quartz corrector lens, forms an image of the entrance slit on the exit slit.

The visible range grating is a 1350 groove per millimeter grating covering from 350 to 800 nanometers in the first order an is blazed at 500 nanometers. The reciprocal linear dispersion is 6.4 nanometers per millimeter. The smallest scale division for this grating assembly is 5 nanometers.

The infrared grating is a 675 groove per millimeter grating covering the range from 0.7 to 1.6 microns is the first order and is blazed at 900 nanometers. The reciprocal linear dispersion for this grating assembly is 10 nanometers.

The image at the entrance slit is reduced in size by a factor of 0.56. The exit slit, therefore, has a width and height which are 56 percent of the entrance slit. Only the wavelength which strikes the exact center of the concave mirror results in an image which falls precisely on the exit slit. All other wavelengths produce images which are to the right or the left of the exit slit. The exit slit width and the dispersion, in combination, determine the bandpass or spectral purity of the system. It is necessary to multiply the width of the exit slit by 1.78 to obtain the proper width of the entrance slit. Using this ratio, only the selected single wavelength can pass through the system at its full intensity.

In order to obtain the best possible accuracy, a spectroradiometer is calibrated at regular intervals. The calibration of the instrument can shift due to such factors as the collection of dust on the optical surfaces or a variety of other random factors. The electronic circuitry of the instrument is very stable and maintains uniform response, but nevertheless the accuracy of the instrument was verified.

The spectroradiometer is calibrated by means of a standard light source which produces known amounts of radiant energy at various wavelengths. At Long Island University, a calibrated ribbon filament low-voltage high-current tungsten lamp is the calibrating standard, and its heavy construction provides relatively good maintenance of its calibration. The lamp is calibrated in terms of spectral energy at various wavelengths at a constant value of electric current through the lamp filament.

Colorimetric Principles and the Characteristics of the Instrumentation Used to Measure Color

Colorimetry, spectrophotometry, and spectroradiometry are terms that frequently confuse those who are not closely connected with the scientific study and analysis of color.

1. Spectrophotometry is the objective measurement of the reflection or transmission characteristics of a material at each wavelength throughout the spectrum in terms of a perfect white reflector or a colorless transmission standard. True spectrophotometry only defines the "color" components of a sample in basic physica language. It does not directly give the apparent visual color which includes the characteristics of the illuminant and the observer's eyes.

2. Spectroradiometry is the procedure for determining the energy distribution of a source of light at each wavelength throughout the spectrum. True spectroradiometry only defines the "color" components of a light in basic physical language. It does not give the apparent visual color which includes the characteristics of the observer's eyes.

3. Colorimetry may be defined as the objective measurement of the

reflection or transmission characteristics of a material suitably weighted for the properties of the illuminant and average human eye color sensitivity. Due to the inclusion of the illuminant and the eye, colorimetry attempts to be subjective in its ultimate data. Perhaps the best illustration of the difference between colorimetry and spectrophotometry is included in the following statements:

1. Two materials having identical absolute spectrophotometric curves will appear identical in color to a human observer when viewed simultaneously under any illuminant.
2. However, it is not necessarily true that two materials having the same apparent color to an observer under any one specific illuminant will have identical spectrophotometric curves.

The basic theoretical requirements of a colorimeter may be summarized as follows:

1. Illumination for opaque (reflecting) samples, or transmission samples under selected standardized conditions of illumination and viewing must be provided.

2. The light normally received by the human eye under the above condition must be separated into three selected primary components and these values measured in magnitude (relative to

some standard) to an accuracy at least equal to that of the eye.

The colorimeter utilized in the experiment was manufactured by Instrument Development Laboratories and used the well established flicker-photometer principle. The flicker system has been in use for many years in spectrophotometers and similar instruments. The main features of the particular optical arrangement used were as follows:

a. Due to the high light sensitivity and gain of the photomultiplier tube, optics of small aperture and short focal lengths may be used, permitting compact design.

b. The design utilizes a minimum of air-glass surfaces and the entire optical system is dust sealed.

c. Precision stray-light stops are used to prevent any light from reaching the optics except from the sample spheres. This is absolutely essential in measuring dark samples.

d. Arrangement is such that the illumination system may be completely replaced by an alternative illumination system.

In the flicker system, the flicker motor drives the optical system so that light from the sample and light from the standard alternately focus on the 1P21 photomultiplier. If light from sample and standard are identical, the photocell output will be unchanged by the flicker. If the two differ, an alternating current will be generated in the photocell circuit. When the light from the optical system reaches the photomultiplier, the light consists of two components:

1. A steady component representing the mean brightness of sample and standard as viewed through the tristimulus filters selected by the operator.
2. An alternating or "flicker" component of magnitude representing the difference in brightness between sample and standard as viewed through the particular source and tristimulus filters selected by the operator.

The colorimeter functions so as to measure the steady component and the difference of "flicker" component and perform the computation necessary to express the difference in terms of percentage difference between sample and standard in terms of reflected or transmitted light. Mathematically, colorimeter automatically performs the computation:

$$\text{Colorimeter Reading} = 100 \left[\frac{\text{Brightness of Sample} - \text{Brightness Standard}}{\text{Brightness of Standard}} \right] + 100$$

Actually, the direct current output of the photomultiplier is amplified and used to control the voltage supply to the photomultiplier in such a manner that the mean current output of the tube is constant for brightness variations of 5,000 to 1. Thus, regardless of the brightness level of sample or standard, the transmission of source or tristimulus filters, or intensity of illumination, a given percent difference in color will give a finite A.C. voltage to the meter. In effect, the sensitivity of the photocell is varied inversely with brightness of light reaching it, just as the iris of the human eye and accommodation of the brain acts to decrease the eye's sensitivity when a brighter object is viewed.