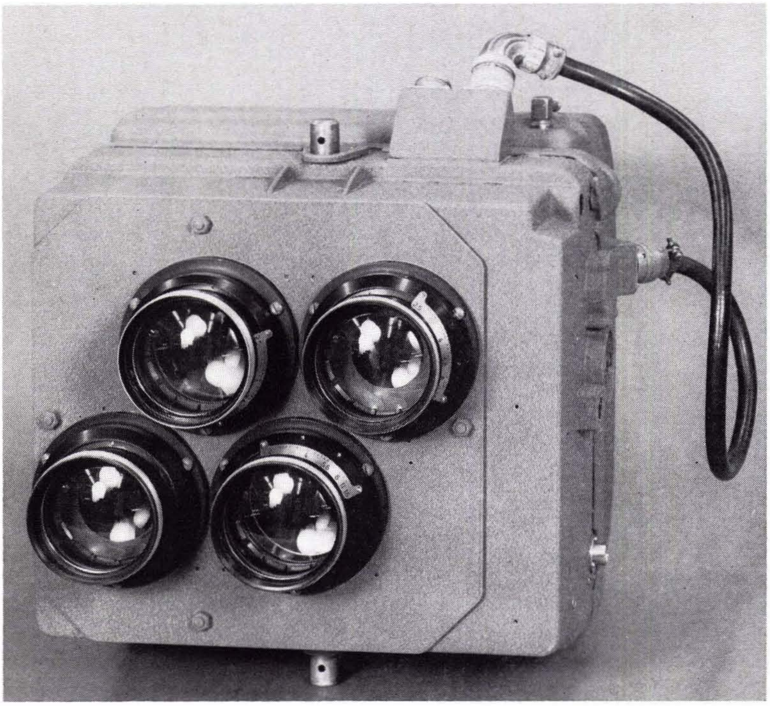

FRONTISPIECE. Four-lens multispectral camera used for research. See page 1026.

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Multispectral Color Aerial Photography

Positive transparencies taken simultaneously with different filters are projected with filtered, variable lamps onto the same screen.

BACKGROUND

MULTISPECTRAL AERIAL photography is conventionally taken by using a number of film-filter combinations to obtain a set of photographs in different bands of the spectrum. The spectrum covered by this photographic technique can include the near ultra violet, the visible and the near infrared. The lower bound of spectral sensitivity is believed to exist at about 260 nm. (nanometer; 10^{-9} meter) due to ozone absorption in the atmosphere. An upper bound exists at 980 nm. which is the current upper limit of the spectral sensitivity of available practical photographic emulsions.

Ground objects usually exhibit a variation in the percentage of radiant energy they

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* A version of this article was presented at the 1966 Annual Convention of the American Society of Photogrammetry at Washington, D. C., March 1966, under the title "Spectral Zonal Color Reconnaissance" when the authors were on the staff of Fairchild Space and Defense Systems, a Division of Fairchild Camera and Instrument Corp.

ABSTRACT: *A camera has been constructed to obtain multispectral photography in four bands in the 360 to 980 nm. portion of the spectrum. Photo-interpretation is accomplished on a companion viewer which presents a composite color rendition of the four photographs by additive color techniques. This camera-viewer system combines spectrophotometric sensing with principles of colorimetry to enable detection of subtile reflectance differences on the ground. Numerous experiments have been performed using models of equipment based on these techniques. The promising results obtained indicate potential applications of this system to agriculture, forestry, water pollution, soil analysis, determination of shallow water depths, as well as to military problems of target acquisition and camouflage detection. The successful application of multispectral technology under great variations of photographic conditions encountered in practical remote sensing depends on precision of the techniques used. Accurate photographic processing is essential for repeatable results.*

reflect. This difference in reflectance in the visible part of the spectrum is what causes the apparent color of an object. A difference in spectral reflectance of an object can be detected as images of different density on a set of multispectral photographs.

To be certain that this density difference is in fact caused by the difference in spectral reflectance of the object on the ground, it is essential that: (1) the camera system be spectrophotometrically calibrated, (2) the spectral distribution of the illumination be known, (3) the spectral bands covered by each photograph be correctly chosen, and (4) the photographic processing be precisely controlled. Under such controlled conditions it *may* be possible to obtain image densities which can be accurately related to the spectral reflectance of the object repeatably and with reasonable precision flight after flight.

Numerous applications of multispectral techniques using a multiplicity of cameras or using one camera to take successive exposures at different times have been reported.[1] A special nine-lens camera was constructed in the USSR as a research tool to establish optimum film-filter combinations to use in photographing selected ground objects.[2] A similar camera has been constructed in the USA originally as part of a multispectral system for detection of surface indications of underground nuclear explosions.[3]

Experiments using multispectral cameras have shown that more information concerning physical features of our environment can be obtained with sensors which operate in spectral bands compared to conventional panchromatic photography.[4] However, many such studies have clearly demonstrated that the human interpreter possesses very low data input and output rates. Herein lies the basic difficulty in using conventional multispectral photography: *it does not discriminate between information collected and, therefore provides the interpreter with much more nonrelevant than relevant data.* The inherent complexity in attempting to compare tonal values on even a few multispectral images and to interpret the results with confidence has been well documented.[5]

A color photograph can be considered as a special type of multispectral photo. In conventional color films the yellow, magenta, and cyan dye layers respond to the blue, green, and red spectral regions of an equal-energy visible spectrum in a proportion fixed by the chemistry of the emulsion. In infrared color film the dye layers respond to the green, red, and infrared parts of the spectrum in a similar manner. When viewed under white

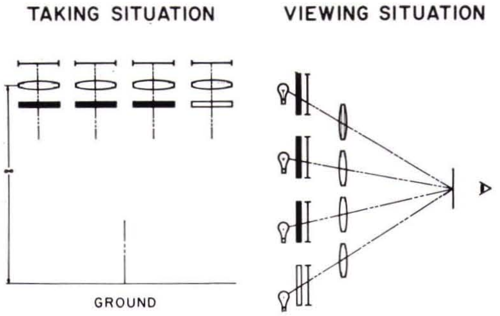

FIG. 1. Schematic representation of the taking and viewing situations for additive color presentation.

light, color photographs *subtract* from the viewing light the undesired colors and the remaining spectral components of light fall upon the observer's eye to produce the sensation of color. The considerable advantages of this subtractive technique of color in aerial photography have been explored in several papers.[6,7]

A number of authors have also pointed out the disadvantages of color aerial photography which are primarily: fixed spectral sensitivity; fixed relative exposure for each dye layer; inadequate exposure latitude; relative processing complexity compared to black and white films; and either (a) a lack of *true* color fidelity to what is seen by a human observer or, conversely, (b) inability to produce significant color differences between objects which have slight spectral reflectance differences.

Color can also be produced by the addition of colored lights rather than by the subtraction of *unwanted* colors from white light. This so-called *additive color theory* can be used to create a composite color image from photographs taken in different parts of the spectrum under certain conditions.[8]

If blue, green and red primary colors are used to illuminate three positive transparencies taken in these respective regions of the spectrum, and these spectral positives have images in identical spatial locations relative to their respective principal points, and if these photographs are optically projected one upon the other so that no misregistration exists, a composite color rendition of the scene will be produced (Figure 1).[9,10] Not only will the primary projection colors be reproduced, but *every* hue will be seen in varying degrees of saturation, and the colors of most natural objects will be recreated rather well. Every image which exhibits a density difference on the individual black and white spectral positives will be seen as a color. If no density difference exists, the composite image will be achromatic (a shade of grey). If the minimum perceivable density difference is about 0.02, not more than 200 shades of grey can be differentiated on a black-and-white photograph, whereas under certain conditions over 7,500,000 *color* differences can be perceived.[11]

THE INITIAL SYSTEM BREADBOARD MODEL

The research described herein was oriented toward developing a Spectral Zonal Color Reconnaissance System* which would provide an interpreter with an image presentation having the following features[12]:

- A "true" color presentation of the ground scene as would be seen by a "standard" human observer.
- False color presentations which would allow very small density differences between multispectral photographs to be seen as color differences.
- A dynamic color presentation which would permit the interpreter to correct for variations in color caused by the spectral distribution of the sun at different times of the day and for different atmospheric conditions.
- A black and white presentation of one or more of the individual multispectral photographs.
- An acceptable level of spatial resolution in composite presentation along with the spectral discrimination achieved by color.
- A minimum amount of time between taking the photograph and subsequent viewing of the composite color image.

A breadboard model of the camera system was constructed using four Fairchild KA-56 panoramic cameras which were used to take photographs in different parts of the spectrum. The four spectral bands initially chosen were: blue (385 to 520 nm.), green (480 to 610 nm.), red (590 to 700 nm.), and infrared) 700 to 960 nm.). The choice of filter bands was made to cover completely the visible spectrum, to approximately the standard observer color sensitivity mechanism of the human eye, and to permit comparison with conventional color and infrared color films.

The four cameras were aligned in an *inner* rack (Figure 2) in such a manner that all the lens optical axes were geometrically normal to a plane common to each exposure slit. The cameras also had the same azimuth orientation to insure that the film of all cameras was transported parallel with respect to each

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* U. S. and Foreign Patents Pending.

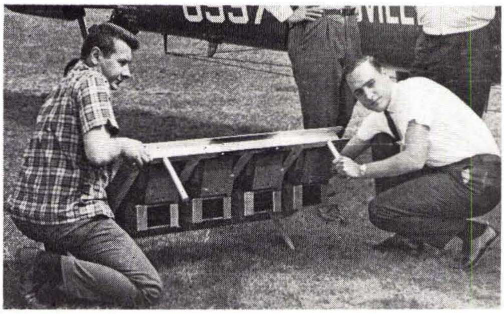

FIG. 2. A four-camera rack of optically aligned KA-56 cameras showing external mountings of the filters.

other. Care was taken to assure that differential distortion and focal-length differences between each of the four cameras was minimized for the spectral bands used.

A control unit was constructed which permitted control of both the exposure of all four cameras simultaneously, as well as each camera individually. This allowed for the variation of exposure with changes in brightness as well as changes in the relative spectral reflectance of the scene.

The objective in using this camera arrangement was to obtain four photographs which contained images in identical spatial locations with respect to the principal point of each individual spectral negative except that the density of similar images would differ from negative to negative. Extreme care was taken to assure that the density of similar images on the four spectral negatives was proportional to the intensity of reflected radiation in the particular interval of radiation *sensed* by each camera. Plus X (EK 8401) film was used with the blue, green, and red filters, and Infrared Aerographic (EK 5424) film with the infrared filter.

The sets of spectral negatives were developed so that the density of any image on each individual spectral negative was a correct representation of the brightness of the object. In addition to compensation for differences in exposure, it was necessary to correct for reduced gamma particularly in the blue negative in order to produce an identical relationship of exposure-to-density on all

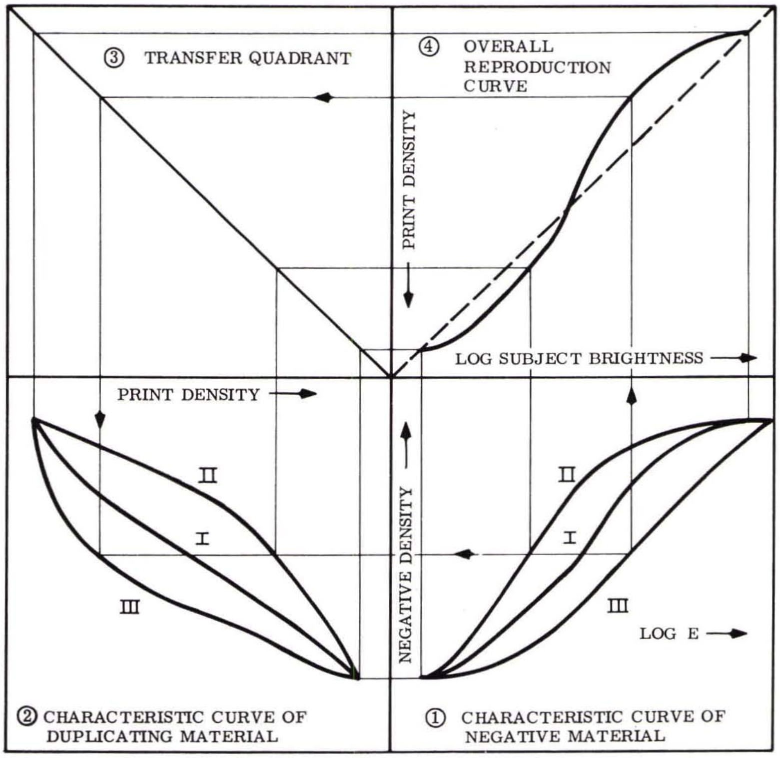

FIG. 3. A tone-reproduction curve for three spectral photographs showing the relationship between regional scene and the final positive reproduction.

FIG. 4. Multispectral additive color viewer.

four negatives. A gamma was chosen to produce medium contrast without excessively reducing the exposure range. Positive transparencies were then made which were also medium contrast with low minimum density (Figure 3).

The composite color rendition of the spectral positives was accomplished by construction of a rear projection viewer using additive color principles (Figure 4). The source of illumination for each of the four spectral positives was controlled in illuminance, dominant wavelength and purity, which in turn controlled the color sensations of brightness, hue, and saturation. Illuminating each spectral positive by a different color of controlled brightness, hue, and saturation, and at the same time superimposing each spectral positive, one upon the other, on a screen by optical projection, produced a composite color presentation.

The understanding of the phenomena of additive color requires a concept of color in a geometrical sense if not in a detailed analytical context. Color can be conceptualized as a cone standing on its apex (Figure 5). The axis of revolution represents the brightness scale. All *black-and-white* photographic images are confined to this one-dimensional brightness axis and thus exhibit a shade of grey. In addition, color has two additional psychophysical variables, hue and saturation, represented in the figure as an angle and distance from the brightness axis.

The image created by the additive color projection of a set of multispectral photos can be established as a position in this color solid by a mathematical treatment. To facilitate color analysis, a mathematical manipulation can further transform the color description to a two-dimensional coordinate position in the chromaticity diagram.[13] In the chromaticity diagram form of presentation (Figure 6), all colors are treated as having the same brightness. The filters used to establish the hue of the viewing colors have chromaticity coordinates shown in the accompanying figure. The triangle connecting these filters is of particular significance. Any color lying within this triangle can be reproduced accurately by additive color techniques.* The filters chosen have the two properties that they provide the maximum area within the chromaticity diagram and the green-red side of the triangle lies close to the locus of pure spectrum colors. This is particularly important if accurate reproduction of color is desired because saturated yellow appears in nature but saturated cyan does not.

A question naturally arises as to how the

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* A detailed mathematical analysis is presented in: Miller, *Principles of Photographic Reproduction*, Macmillian (1943).

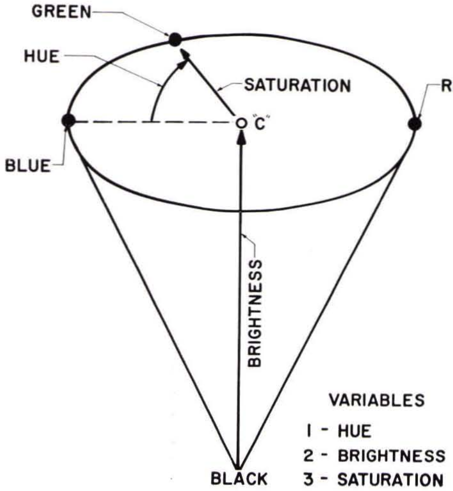

FIG. 5. Color solid indicating the geometric interpretation of color.

position of an image in the color solid can be manipulated. A schematic view of the viewer breadboard model shows how this is accomplished (Figure 7). The four spectral positives are contained in a single film plane. Each is illuminated by a *brightness* lamp, which contains a filter in the optical path, and a *saturation* lamp. The light from the *brightness* lamp controls the brightness of the illumination of each spectral positive. The filter establishes the *hue*, and the illumination of the *saturation* lamp controls the amount of desaturation. Manipulation of these color variables controls the apparent color of the composite image on the screen.

EXPERIMENTAL RESULTS USING THE INITIAL BREADBOARD

The camera breadboard model of four KA-56 panoramic cameras was flown in September 1964 on Long Island, New York. The solar angle at the time the photography was taken was approximately 30° with scattered cloud cover and moderate haze.

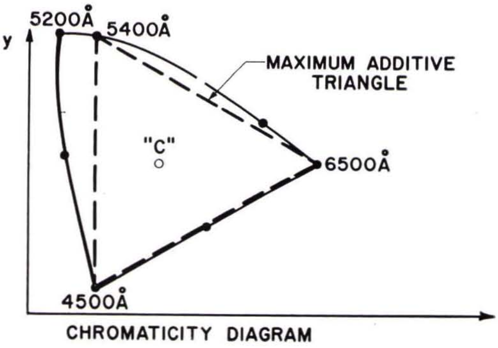

FIG. 6. Chromaticity coordinates of viewing filters.

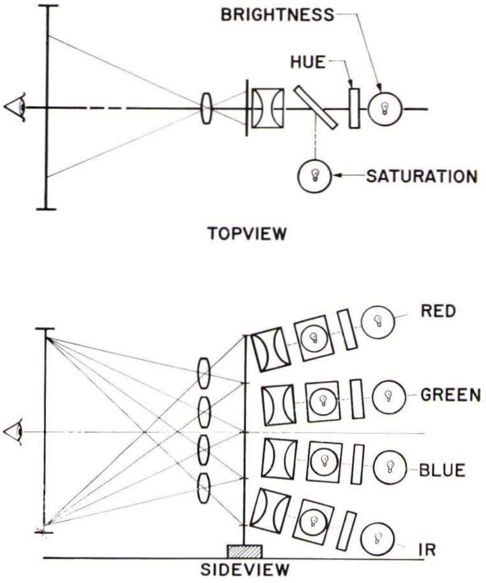

FIG. 7. Schematic diagram of the additive color viewer.

More than thirty experiments were conducted in which the spectral negatives and positives were processed with various characteristics. Each set of experimental photography was placed in the viewer, aligned, and analyzed for registration and color characteristics.

The best evaluation of the experimental results can be achieved by looking at the viewer screen. However, in order to convey to the reader an indication of some of the results of these tests, several experiments were recorded by taking color photographs of the composite image on the viewer screen.

The set of photographs in Plate 1 shows the individual black-and-white spectral positives as they appeared on the viewer screen. These four positives are indicative of conventional multispectral photography discussed previously, in which the interpretation procedure is to compare the density differences of selected objects on the individual photographs.

If the blue, green, and red spectral positives are projected each with its respective primary to form a composite image on the viewer screen, a *true* color rendition is seen (Plate 2a). The color characteristics of the composite rendition can be varied by adjustment of the brightness, hue and saturation of the source of illumination for each spectral positive.

If the green spectral positive is projected as blue, the red as green, and the infrared as red, the standard *camouflage* false color rendition is observed (Plate 2b). Living deciduous foliage (a mixture of oak and maple) appears as red, dying foliage as magenta, and dead foliage as a green-brown color.

On examining the reproductions of these results, the reader should note that both composite color renditions show all density differences between the individual spectral positives as colors. Images which have the same density on all spectral positives, such as shadows, are a shade of grey in the composite presentation.

Plate 3 shows two multispectral color renditions of a stand of oak, some of which have been cut. Cutting was timed to occur from two weeks to two hours prior to the time of photography. The chromaticity coordinates of the standard camouflage color rendition of living (uncut), dead, (cut more than two days) and dying (cut two hours to two days) foliage are shown. The second composite presentation shows a false-color space achieved by combining all four spectral positives. In this latter rendition, the dead trees are shown as red, the dying are pink, and the live as blue. The more important fact is that the color-signature overlap between the chromaticity coordinates of the live and dying categories which occurred in the standard camouflage rendition has been eliminated in the second false color space.

A capability of the viewer to allow control of color in order to achieve a target detection was also demonstrated as a result of this experiment. As can be seen in Plates 4a and 4b, it was possible to *wash out* the chromatic noise due to variations in reflectivity of natural objects while at the same time to enhance the apparent color of a man-made object, in this case a green vehicle.

Another flight test of significant interest was performed in May 1965. The targets consisted of equipment in a typical military deployment camouflaged by various types of military camouflage nets. These nets were embedded in foliage cover and generally in deep shadow. Two reproductions (Plates 4c and 4d) show a comparison of a pahchromatic photograph (EK 8401 film with Wratten 25 filter) taken at 750 ft. altitude, and a color-multispectral rendition of the same scene. Note the greater target detection capability of the composite color presentation particularly the two nets embedded in the trees.

More recent flight tests have also demonstrated the possible usefulness of this technique for water polution studies. Plates 4e and 4f show both a multispectral color and an Ektachrome color photograph of Indian Creek in Miami just after hurricane Inez in October 1966. The presence of salt water can be detected as green in the multispectral color rendition where the presence of color shift is not discernible in the conventional color photograph.

RECENT EQUIPMENT FOR RESEARCH

A four lens camera has been designed by the authors and manufactured by Fairchild Space and Defense Systems to take multispectral photos in four bands from 360 nm. to 980 nm. (Frontispiece). The spectral region covered by the camera includes part of the near ultraviolet, the visible, and part of the near infrared. Fairchild has also manufactured a companion additive color viewer which projects the set of four spectral photographs on a screen to form a single composite color presentation for interpretation.

The camera takes a set of four spectral negatives at exactly the same time and records all of them on one piece of film.* The spectral regions recorded may be any three bands in the ultraviolet-visible, and one band in the infrared, without making any adjustment to the camera. Accommodation of more than one infrared band, if desired, can be made by an optical adjustment. If no prior knowledge exists of the spectral reflectance of a target, a set of broad band filters which overlap throughout the spectrum are used. In those instances where spectrophotometric analysis has isolated wavelength regions and where the phenomena may be spectrally detected, appropriate filter-film combinations can be used which, together with the transmission characteristics of the camera lenses, will permit accurate multispectral photography in the particular wavelength bands. As each band is photographed through its own lens, it is possible to obtain the correct exposure of each negative for the spectral radiance of any scene. This control of exposure for all four bands permits repeatable accuracy under a wide range of illumination and ground reflectance conditions.

Each one of the four spectral negatives, which together comprise a set of multispectral photographs, is taken at exactly the same

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* The camera also has a capability of using four separate rolls of film by changing the magazine.

time by four matched lenses. As the optical axes of all the lenses are normal to the film plane, four spatially identical negatives are produced. All the images appear in identical coordinate positions as measured from the principal point of each photograph.

The viewer illumination system is designed to give the interpreter control of the dominant wavelength (hue), purity (saturation), and brightness of the illumination *source* for each spectral positive. He can adjust any one of these three variables for each of the four spectral bands to achieve the desired color space for viewing. In any color space, the composite additive color photograph shows all density *differences* between the individual spectral positives as colors. Those images that have the same density on all spectral positives will be achromatic (colorless) in the composite additive color presentation. Images which may escape detection because the density differences may be too slight if the film is viewed on a light table are almost always easily identified by difference in hue, brightness, and saturation of the image in relation to its background in the composite additive color presentation.

This method of abridged spectroradiometric sensing of radiant energy reflected by ground objects in the 360 nm. to 960 nm. spectrum and subsequent colorimetric analysis of the composite additive color image is designed for rapid and accurate photointerpretation. The rapidity is obtained by using a unitary piece of film upon which the principal points of the four photographs have been precisely located with respect to the film edge. This permits automatic registration of the composite additive color image after the interpreter has checked the registration of the first frame in the roll.

REQUIREMENTS FOR ACCURATE MULTISPECTRAL PHOTOGRAPHY

All of the experiments performed to date have demonstrated the absolute necessity for precise photographic technique in order to obtain repeatable results in different geographical areas under different photographic conditions.

The first requirement for accurate multispectral photography is to establish the spectral reflectance of the ground object. When subtle differences are to be determined, object-to-background spectral reflectivity must be established, and the spectral bands where relative differences in reflectance occur must be located. A spectrophotometer with a diffuse reflectance attachment has been used for this purpose. However, as all such instruments integrate the energy reflected by the sample, preferential directional reflectance at particular wavelengths is not recorded. The airborne camera is a perspective sensor which records the directional reflectance characteristics of a ground object. In many instances considerable difference has been found to exist between total diffuse reflectance of an object as recorded by a spectrophotometer and the reflected energy measured at a specific angle of incidence and reflection. The spectral distribution of the solar irradiance falling on the ground at the time of exposure can be established by using a portable recording spectroradimeter.

The camera must be spectrally calibrated in order to relate the energy falling on the film plane to that entering the lens. This requires calibration of the spectral distribution and magnitude of radiant energy as a function of field angle of the camera lens. The camera system must be designed to obtain spatially identical photographs. This means that the focal lengths and distortions of the lenses must be identical for each wavelength band. All photographs must be taken at the same instant of time to avoid shift in relative position of the image on the spectral negatives due to aircraft angular motion.

Film processing is critical for accurate results. So-called panchromatic films have different characteristic curves as a function of wavelength. When the film is processed, each spectral band can be expected to have a different relationship of log exposure (or radiometric equivalent) to density. This difference in the characteristic curves of multispectral photos can be corrected by differential processing, or eliminated by printing on polycontrast materials. These gamma differences cannot be incorporated in a *standard* definition of chromaticity of a ground object because density variation will occur in the particular spectral bands due to exposure differences, and will not be necessarily caused by a difference in spectral reflectance.

Using positive transparencies for additive color projection creates a dilemma between contrast and exposure latitude. The higher the contrast the more saturated the color, but the more compressed the scene brightness range, and vice versa. In general, good color reproduction is achieved using positives with low base density and moderate to high contrast.

If the spectral positives are to be viewed in additive color, the viewer optical design must allow accurate registration and be free of color

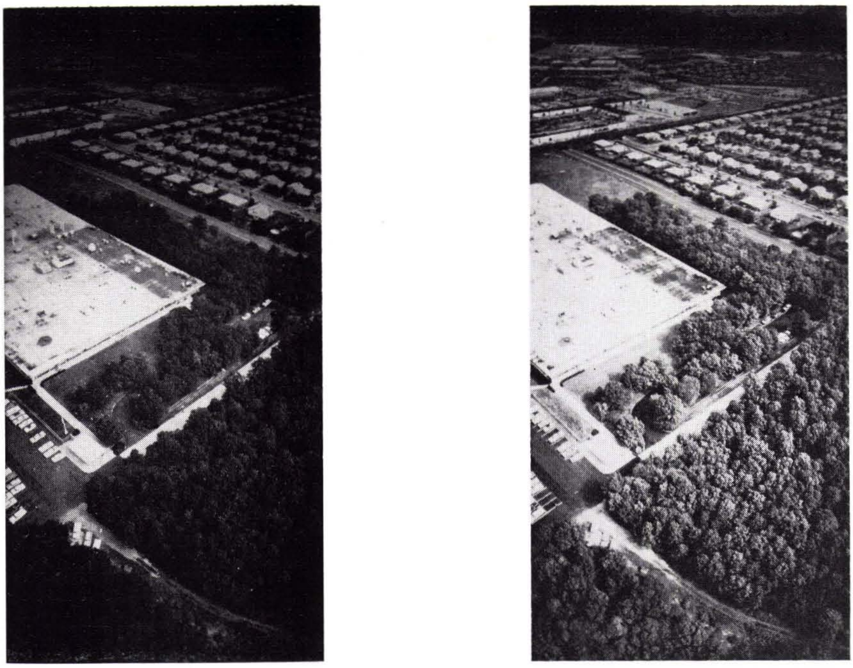

PLATE 1a. Spectral photograph in the blue band (325 to 520 nm.).

PLATE 1b. Spectral photograph in the green band (480 to 610 nm.).

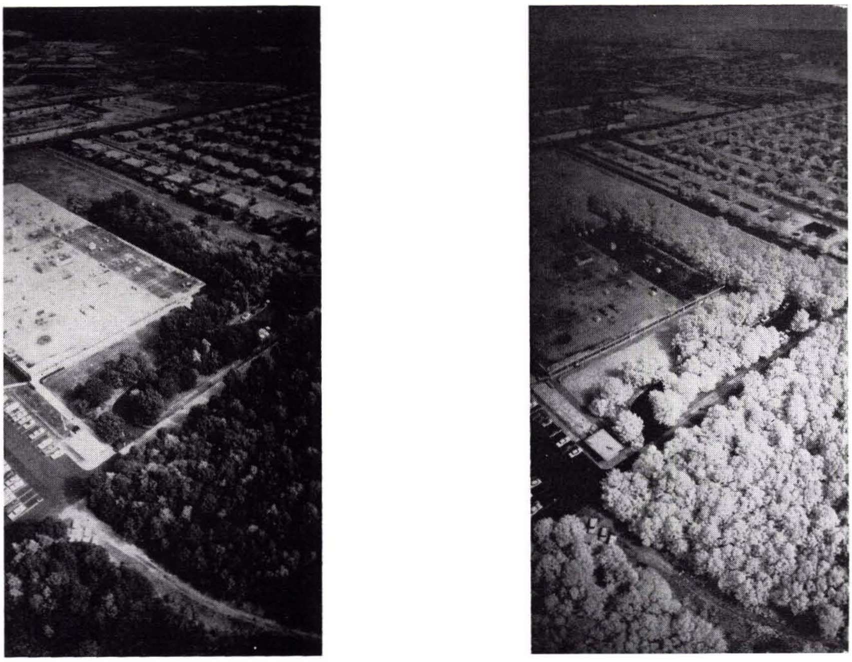

PLATE 1c. Spectral photograph in the red band (590 to 700 nm.).

PLATE 1d. Spectral photograph in the near infrared band (700 to 980 nm.).

PLATE 1. Four multispectral photographs each having images in identical spatial location with respect to the principal point.

PLATE 2a. Composite "true" color rendition of blue, green, and red spectral photographs (enlarged 35 mm. color negative reproduction of viewer screen).

PLATE 2b. A composite false color rendition of green, red, and infrared spectral photographs (enlarged 35 mm. color negative reproduction of viewer screen).

PLATE 2. Reproductions of two multispectral color presentations achieved by superimposed optical projection on the viewer screen.

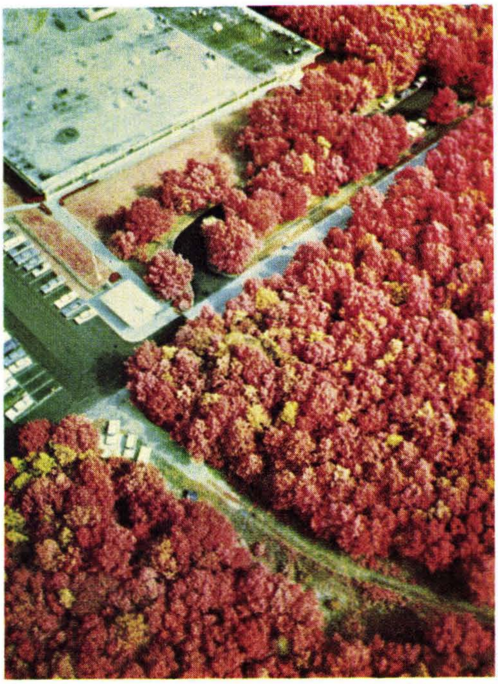

PLATE 3a. Standard camouflage detection false color rendition using green, red, and infrared spectral photographs.

PLATE 3b. False color space using four spectral bands which exhibit improved color separation.

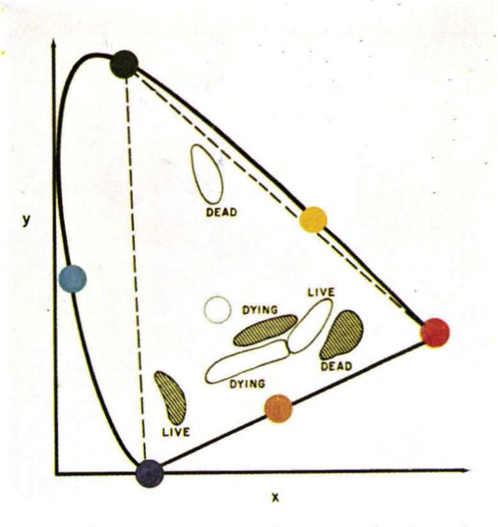

PLATE 3c. Chromaticity diagram showing the colors of live, dying, and dead deciduous trees.

PLATE 3. The infinite variety of color rendition results in improved detection of vigor of foliage.

PLATE 4a. Natural color view of green vehicle protruding from trees.

PLATE 4b. False color target detection mode showing chromatic enhancement of vehicle and suppression of natural background.

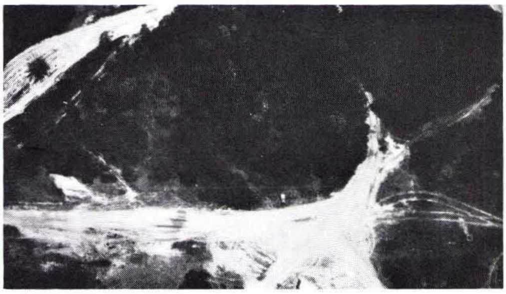

PLATE 4c. Plus X photograph with Wratten 25 filter of test site.

PLATE 4d. Multispectral color presentation of test site. Note detectability of camouflage nets in trees.

PLATE 4e. Aerial Ektachrome photograph of Indian Creed after Hurricane Inez.

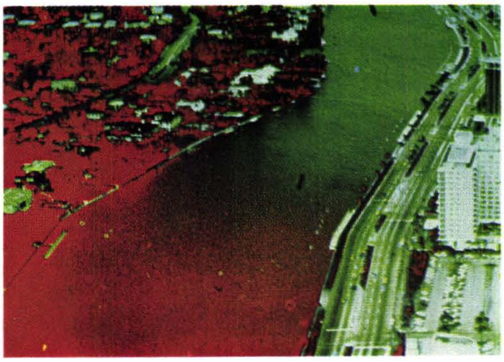

PLATE 4f. Simultaneous multispectral color photograph showing differences in water purity.

errors. Manipulation of the color variables of hue, brightness and saturation must be calibrated and not be distorted by shifts in color temperature of the illuminant as the brightness of the projection lamps is varied.

The above precautions will not guarantee that all interpreters will identify the color of an image as being the same under different viewing conditions. This can be explained by the fact that a color photograph does not conform to colorimetric specification of a two-degree circular field of color in an otherwise dark field. It is known that spatial relationships within the visual field can affect hue, brightness, and saturation of colors. Variation in the angular size of an image is known to cause a change in apparent color. Isolated images of the very smallest angular sizes produce no hue response at all. The position of an image in relation to other images can also cause apparent color changes. There is a tendency for the visual mechanism to accentuate the color difference in objects juxtoposed in spatial position (simultaneous contrast enhancement), but an image-directed attitude on the part of the interpreter tends to reduce contrast enhancement effects.

These psychological aspects of color viewing make the final specification of the color of an image in objective mathematical terms necessary. While the color of the presented image can be manipulated to suit the desires of the interpreter, unambiguous color specification independent of a particular interpreter-photograph relationship is considered necessary to achieve reproducibility of results under a variety of photographic conditions.

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