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Simple Multispectral Photography and Additive Color Viewing

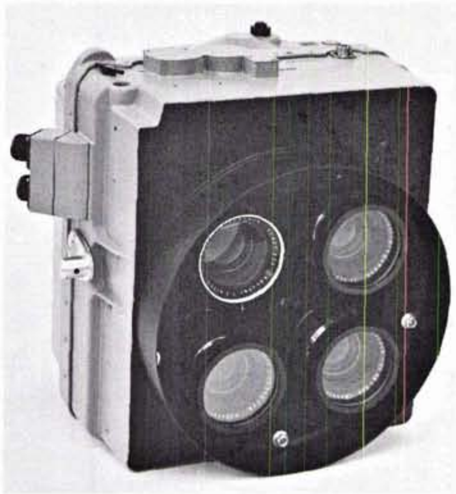

Fig. 1. I²S Multispectral Camera, Mark 1.

High-quality imagery is provided for routine interpretation, research and training without excessively stringent and costly specifications.

(Abstract on next page)

Introduction

Much of the published literature on multispectral photography and additive viewing systems discusses work and equipment which is either very complex, or apparently very simple. At one end of the scale, techniques of microdensitometry, pattern recognition, image processing by computer, quarter-million dollar cameras and optical viewers, and similar sophisticated approaches are described. At the simple end, many systems based on three or more off-the-shelf 35-mm or 70-mm hand cameras and conventional slide projectors have been discussed.

Either way, the impression is given that much remains to be done before standard, economical multispectral photography and additive display will be feasible for everyday routine tasks. Such is not the case; simple production equipment is available commercially and has been put into use in the United States and many foreign countries during the last three years.

Reasons for Multispectral Photography and Additive Color Viewing

The chief reasons why the multispectral technique is used is that with black-and-white films and conventional processing, the benefits of natural- and false-color films can be obtained rapidly at less cost. As normal black-and-white negative and positive processes are used, more exposure latitude is possible. Moreover, a much greater flexibility is available to the user in selecting hue and brightness levels in the image being analyzed, to emphasize best the phenomena of interest. Where adequate sensitometric control is available, multispectral images can be used for abridged spectro-photometry with more accuracy than is possible with color films.[1]

Need for Practical System Parameters

The scope and complexity of multispectral research and development, and the technical magnitude of programs such as ERTS, tend to intimidate the average user in committing himself to simplified multispectral equipment and procedures. Certainly, a great deal of intensive research remains to be done to wring the utmost value from the potentials of remote sensing; but this will be restricted to a few centers, small groups of specialists and large investments in facilities and equipment.

Simple systems must be developed to certain specifications, but care should be exercised before accepting many of the cautionary statements voiced by some, who would per-

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ABSTRACT: *A multispectral camera and additive color viewer system must satisfy certain optical, mechanical and performance specifications if it is to produce imagery of a quality, and in a form useful for aerial and earth-resources surveys, research, or training applications. The equipment should provide timely results on an economical basis in a convenient, standard form. Published information describes systems which are either prohibitively expensive for the average user, or simplistic to a degree which fails to meet the requirement. Some technical parameters have determined realistic specifications for an economical production multispectral system proven in wide use in the United States and many foreign countries.*

suade us that excessively stringent conditions must be satisfied to make even simple multispectral systems efficient. Control over illumination to a few percent in viewers, resolution and registration four or five times better than visual acuity, establishing exact CIE color coordinates, narrow-pass camera filters and dozens of spectral bands, are but a few examples of requirements which are purely academic for 99 percent of the image analyst's work. What, then, are the parameters for establishing within economic limitations a multispectral camera-viewer system for everyday use? Here are some of the key determining factors.

Off-the-Shelf Cameras & Projectors

MULTI-CAMERAS

Simplicity and economy are generally closely related. At first glance, the simplest solution is to use several good-quality commercial hand cameras and slide projectors to form a multispectral system, and a number of experimenters have taken this route. However, it is soon found that the technical operating problems become quite complicated, the system is anything but simple, and standardized results are impossible to obtain.

Among the major faults is camera mounting; image rotation is almost inevitable between the several cameras and has to be corrected somehow during projection, as the eye is very sensitive in detecting rotational misregistration. The most common problem is the difference between the scales of images taken in different spectral bands. Production hand-camera lenses of the same make, even though well color-corrected, can vary by a few percent in focal length from lens to lens, and between spectral bands. These errors must be corrected if several images are to be registered as a composite.

Multi-camera arrays use separate rolls of film, often of different types, in each camera. Processing times are usually different among the spectral bands, and accurate sensitometric control measures are multiplied by the number of negative films and positive prints involved. Discrepancies are apt to occur. The headaches of search and retrieval in finding matching sets of spectral images among a number of rolls of film is, of course, well-known.

MULTIPLE PROJECTORS

Several commercial projectors are usually adapted in some kind of common mounting to project the spectral images in registration on a screen. Few projectors have built-in 70-mm roll-film facilities, and individually cut film chips must be mounted in each projector.

Few projectors have lenses of matched focal lengths, low distortion, good color correction, or project a uniformly flat field. Aligning images from three or four projectors in x, y and rotation, while attempting to correct for scale differences in the camera by the projector, are formidable tasks. It can be done, but few image sets can be handled at one working session.

As with multi-cameras this solution is not efficient or convenient.

SIMPLE MULTISPECTRAL CAMERA AND VIEWER

The major problems discussed above are eliminated by the production Camera and Viewer system illustrated in Figures 1 and 2. The four lenses in the camera are mounted in the same lens cone, ensuring absolute boresighting and completely obviating rotation of images relative to each other, as all 3½-inch square images are exposed on a single roll of 9½-inch film. The lenses have been selected in matched sets by their measured focal lengths in the blue, green, red and

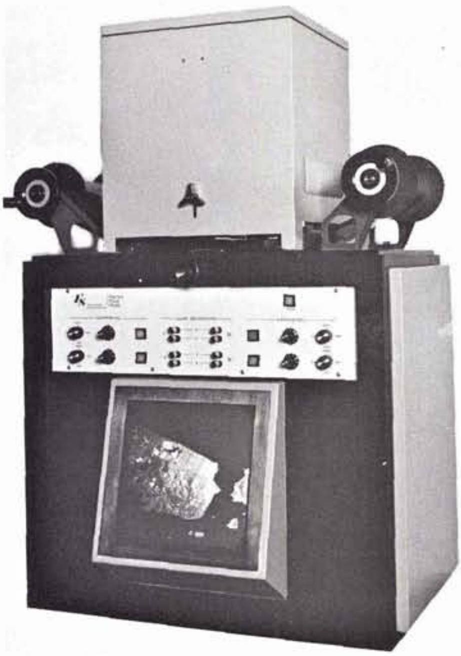


FIG. 2. I²S Mini-Addcol Additive Color Viewer.

infrared spectral regions, eliminating the need for scale corrections in viewing.

The characteristics of the film emulsion* are such that processing in conventional developers permits accurate color separation and matching gammas for the blue, green and red images. The higher gamma in the infrared region accentuates chlorophyll effects.

All images remain together during reproduction, print processing and display, and the search and retrieval problem is minimized.

The Viewer shown in Figure 2 only requires x, y image motions for registering the four images; however, a special adapter plate is provided for ERTS, or other 70-mm imagery, in which images can also be rotated for registration. Each of the four projection lenses is fitted with blue, green, and red filters, as well as a clear position, enabling false-color combinations to be formed which are not possible with color films. Other versions of this viewer have projection capabilities.

* Kodak Infrared Aerographic Film 2424, which is sensitive from the ultraviolet through the visible region, and into the infrared to about 900 nm.

KEY PARAMETERS FOR AN EFFECTIVE SIMPLE SYSTEM

As with any other aerial photographic operation, elements of the system extend from image acquisition through to data reduction, and involve equipment, techniques and reactions of the human analyst. These interacting elements require further discussion, to define key parameters.

CAMERA FILTER BANDS

How critical is the spectral position and band-pass of a filter; must special filters be used for detecting particular subjects? In general, the answer is that normal three-color separation filters and an infrared record will satisfy almost all multispectral requirements.

Terrain and ocean subjects have no unique spectral signatures in the same meaning that spectroscopists use; there are no narrow-band spectral spikes distinctly identifying elements and colors one from the other, but rather a gradual change in reflectance values, usually undulating at low amplitudes of radiance across the spectrum which the photo material is capable of recording. An exception is the strong but broad-band infrared reflectance of broad-band infrared reflectance of chlorophyllic substances.

Many subjects have marked reflectance differences according to season, quality of illumination, time of day, atmospheric Miė and Rayleigh effects, polarization, rainy and drought conditions, and other variables which may be unknown, unpredictable and usually cannot be accounted for. For example, spectral measurements made on a leaf may be quite different from those made on a tree full of the same leaves, or the wind may blow, turning the underside of many leaves toward the spectroradiometer, yielding a still different spectral measurement. The same plant species in a single scene may show large changes in spectral reflectance, because of changes in growth caused by differences in elevation, prevailing winds, local temperature and available moisture.

Because of these unpredictable differences in spectral reflectance, coupled with unknown atmospheric effects, using many, or narrow spectral filter bands complicates rather than clarifies multispectral interpretation, and such systems have been largely abandoned except for research under controlled conditions. For general interpretation, experience shows that recording the conventional blue, green and red primaries satisfies all major multispectral filter requirements. The addition of an infrared record permits the reconstitution of natural, false-color IR and a wide range of color effects.

A set of spectral bands which yields excellent results is shown in Figure 3. The 57A filter has a passband similar to the ERTS-1 green RBV Camera, and the 25 filter to the RBV red record. The 88A extends further into the infrared than the equivalent ERTS-1 RBV.

IMAGE FORMAT AND RESOLUTION

The camera (Figure 1) takes four 3½-inch square images; each having an area 240 percent larger than a 70-mm format. A magnification of 2.6× enlarges the image to 9 inches square on the screen of the viewer shown in Figure 2. A 70-mm format would have to be enlarged 4× to become 9 inches square. The greater magnification not only emphasizes the appearance of granularity, but requires a higher initial film resolution to record the same spatial detail at the same image scales on the viewer screen.

Multispectral systems use Kodak 2424 Infrared Aerographic emulsion for the IR record, which resolves 80 line/pairs/mm with a high-contrast target and 32 l/p/mm at target contrast of 1.6:1. These are limiting factors and are independent of lens focal length. The resolution of the eye is 7 to 10 l/p/mm.

At a magnification of 2.6×, 32 l/p/mm become 12 l/p/mm on the viewing screen, but at 4× this drops to 8 l/p/mm. Retention of the higher resolution is important because the resolution of spatial detail is intimately connected with the subject contrast, color, form and background. Recording spectral information is also a part of this condition. At the limits of optical resolution, the lens fails to resolve an object point as a coherent bundle of energy, or at the limit of film resolution the imaged point is scattered among grains of silver halide, or both effects combine. But the image carries spectral as well as spatial information. If spatial resolution limits are exceeded, spectral energy information is degraded, and the accuracy of spectral recording is affected.

Multispectral photography should be flown at a scale large enough to ensure that important ground spectral detail is imaged within system resolution limits.

The contrast of subjects may also vary between spectral bands, indirectly affecting apparent spatial resolution. A white object reflecting green and red energy equally, placed on a green background, will have a lower contrast ratio in the green than in the red spectral image. As the green background has little red reflectance, the red spectral band sees the white object as contrasting strongly against its background, but in the green record the contrast ratio will be reduced considerably by the energy reflected from the green background and the white object.

It is feasible, therefore, to obtain more than adequate spatial and spectral resolution from a simple optical-film combination, which will satisfy the great majority of multispectral interpretation tasks, as well as training and research.

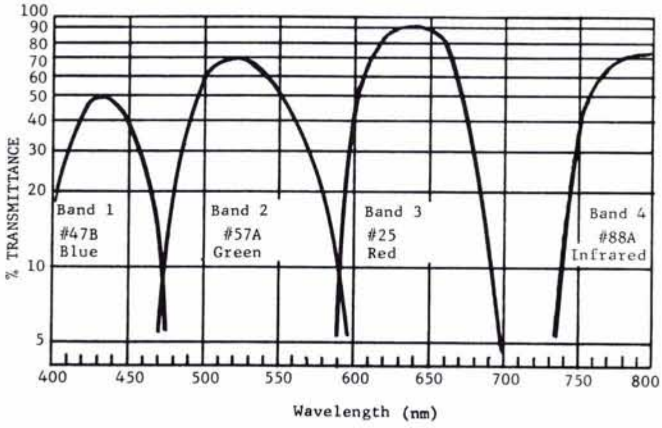


FIG. 3. Typical Wratten filters used in the I²S Multispectral Camera, Mark 1. Interference filters block the longer wavelength transmission of the blue, green and red filters. Other filters and passbands may be selected, such as an 89B on Band 4 which has 11 percent transmission at 700 nm and opens rapidly into the infrared region.

BASIC EXPOSURE

Multispectral camera exposures (where the same shutter exposes all bands at a given speed) is adjusted by setting lens apertures. Exposure in each band should be sufficient to place the subject reflectance range of interest on the straight-line part of the film response curve for each spectral band. The balance should be such that a white object, reflecting equally throughout the 400-nm to 900-nm region has the same normalized density in the processed negative. If exposure imbalance is excessive, some spectral records will have little density and others too much, making a reproduction balanced for viewing difficult to print.

Based on extensive operational experience, the normal aperture settings for 2424-type film at 1/400 second are indicated in Table 1. With certain conditions and subjects, a change in aperture relationships may be advisable to optimize the multispectral records, or to facilitate reproduction. For example, in tropical regions haze and strong chlorophyll effects may require Band 1 to be exposed at $f/8$, and Band 4 at $f/16$, at altitudes of 10,000-20,000 ft.

TABLE 1. NORMAL APERTURE SETTINGS FOR KODAK AEROGRAPHIC FILM 2424 AT 1/400 SECOND

	Altitudes to: 20,000 *ft.*	65,000 *ft.*
Band 1–47B, blue	f/5.6	f/8
Band 2–57A, green	f/4	f/5.6
Band 3–25, red	f/4	f/5.6
Band 4–88A, infrared	f/11	f/11

Exposure determination is no more complicated than with color aerial photography, but should receive the same attention. Once a satisfactory balance is found, a table such as that in Figure 4 may be used. Aerial exposure calculators should be used only for determining sun altitude because film speed data and other factors are calculated for conventional aerial photography and are not applicable.

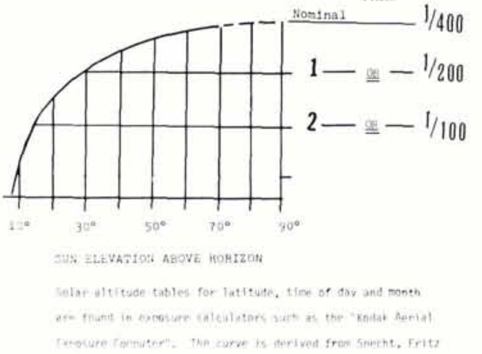


FIG. 4. Relation between solar altitude and approximate changes required in f/stops or shutter speed for average conditions at 10,000 feet.

FILM PROCESSING, GAMMA AND EXPOSURE BALANCE

Kodak 2424 emulsion, if processed as recommended here will reproduce the blue, green and red images at almost the same gammas (1.60), providing excellent color separations. The infrared band has a higher gamma, but this is advantageous in detecting and emphasizing reflectance variations in this invisible region. However, in balancing exposure of the IR band relative to the others, the higher IR gamma must be taken into account. As the gammas between the first three bands and the IR are in the proportion $1.60/1.80 = 0.89$, the density of the white object in the IR band, multiplied by .89 should be equal to densities for the same object in the other bands when relative exposure balance has been achieved for all four. Film processing data are given in Figure 5.

FILM POSITIVE

The positive roll film transparency for additive color viewing generally should be printed on a high-contrast emulsion such as Kodak 2430 Aerial Duplicating Film, processed to a gamma of 2.0 or more. The product of the film negative and positive print gammas determines the degree of chromatic saturation obtainable in additive viewing, and should be 3.0 or more, as in most aerial color films.

ADDITIVE COLOR VIEWING

Viewing any kind of color reproduction involves many physio-psychological factors, and it is natural that specification of additive color display and control leads to controversy. The inclination, in making trade-offs between economy and precision, is to lean heavily toward precision to an extent not justified by facts.

In the first place, visual evaluation of color is a subjective process; a relative rather than

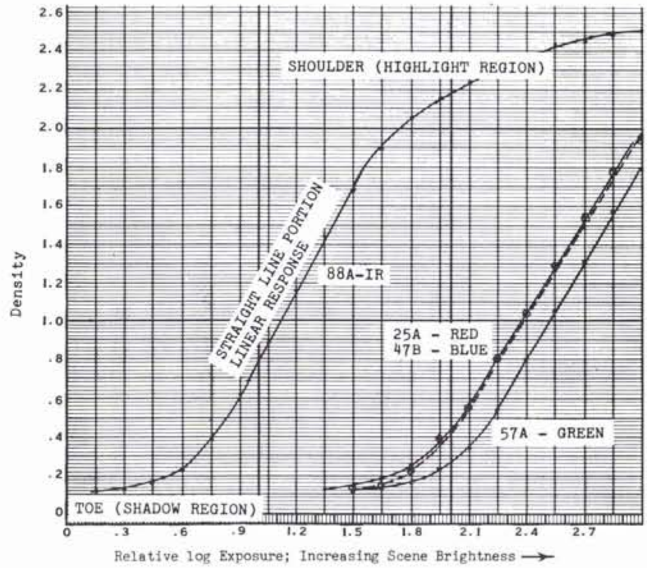


FIG. 5. Spectral response curves for Kodak Infrared Aerographic Film 2424 (Estar Base), Mil Designator 11-24-74f, D-19 developer, 12 min 68°F (20°C). Exposure 10^{-2} sec., EG&G MK VI Sensitometer, lamp calibration traceable to NBS Standard. Straight-line regional gammas: Band 1, 47B, blue, 1.60; Band 2, 57A, green, 1.66; Band 3, 25, red, 1.60; Band 4, 88A, IR, 1.80. Similar results are obtained with 641 chemistry in Versamat processors, 2 racks in developer, 5 feet per minute, 85°F (29°C).

an absolute function. Perception and acceptance of natural color images are conditioned by the individual's memory of object colors seen every day. The adaptability of the eye and memory is such than even two-color (blue-green and orange) additive systems appear to synthetize a wide range of color.

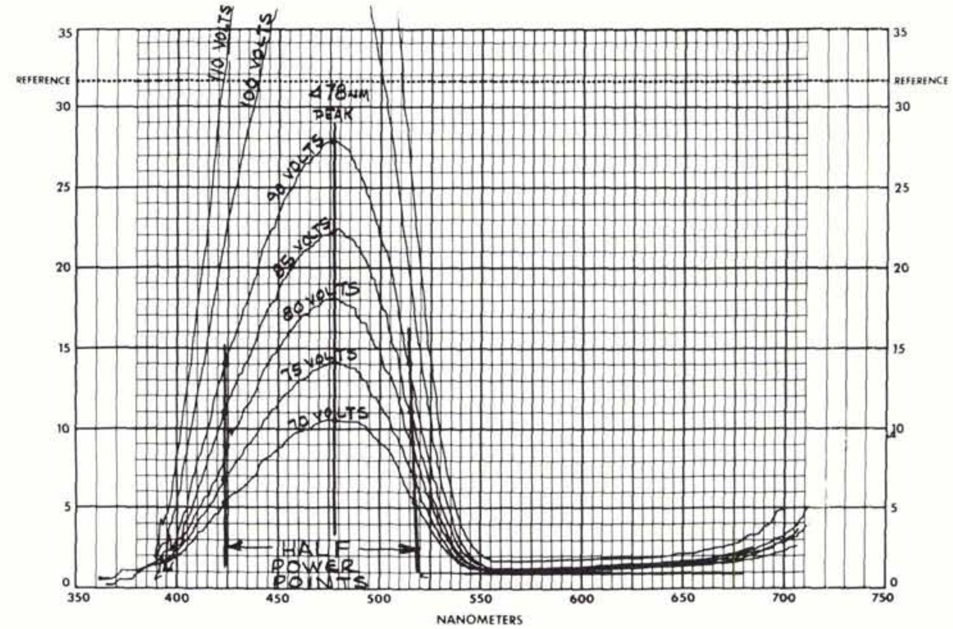
Filters used in multispectral photography are designed to recreate natural and color-infrared or other effects, but the same filters do not have to be used in additive color projection to synthetize color imagery completely effective for viewing and analysis. An absolute color match between the original and the image is seldom possible, or even desirable.

It is well-known in color work that a preferred reproduction of colors is usually required, where departure from equality of appearance between the original and the image is necessary for optimum perception of the scene. This applies to paper prints, projected color transparencies, color television, and additive color viewing systems.

For example, the ground viewed from an aircraft at altitude appears blueish because of atmospheric light-scattering in the blue region. Some color hues are altered and contrast reduction occurs. *Natural* color aerial films are purposely designed to improve contrast rendition, and a series of haze filters may be used to suppress excess blue. The color transparency is thus deliberately shifted from real values to a color balance closer to everyday appearance, and the interpreter's memory of grass as green, not blue-green. In additive viewing, the effect of using a haze filter is given by adjusting relative intensities between the blue and green bands.

The eye can discriminate about 150 color hues, and several million color differences under test conditions. In ordinary color viewing other factors control the situation. Apparent hue, saturation and brightness are affected by the visual angle; that is, as detail becomes small and its shape varies, different hues may actually seem identical. Even large areas of the same hue, but displaced by some distance from each other on a viewing screen can seem different against different color backgrounds.

Although CIE tri-stimulus measurements of color images may be read off the viewing screen, for technical reasons the standard tri-stimulus spectral light sources cannot be reproduced exactly in an additive projection system, and it is unrealistic to specify that this be done. It should be remembered that



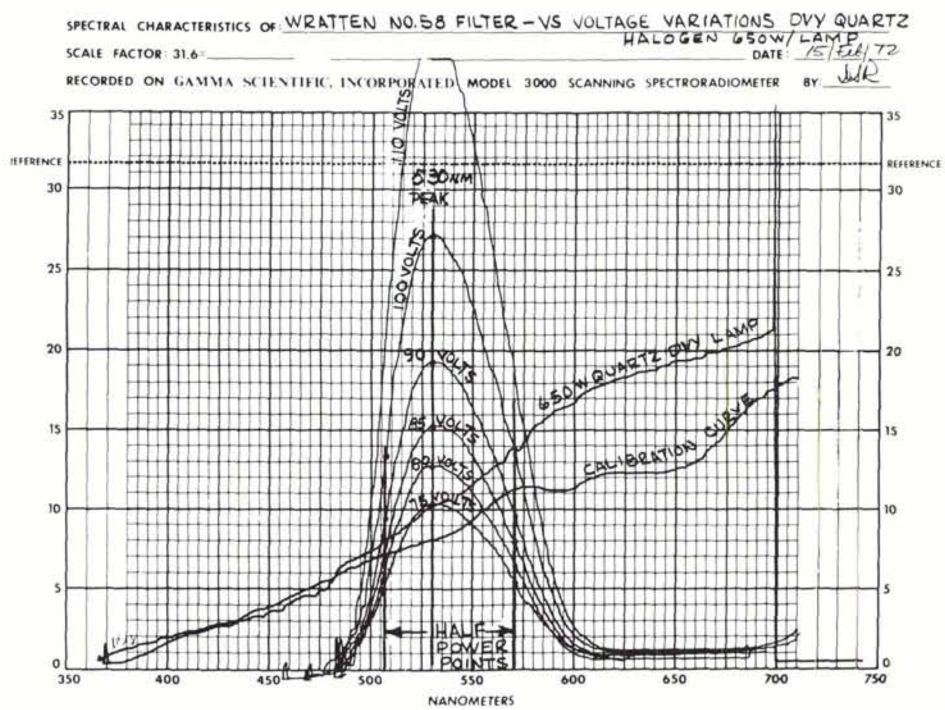


FIG. 6. Spectral radiometric measurements on two filters where light-source voltage is varied. Note that peak wavelengths and band-pass half-power points do not change with voltage. The upper diagram was for a Wratten No. 47A filter and the lower for a No. 58.

CIE coordinates measure a sensory impression of color and are not necessarily a sound guide for exposing photographic copies of the screen image. Photo materials are likely to respond to spectral radiant energy in a different way than the eye, and will record a different color balance.

Color de-saturation by bleeding white light into a spectral channel has been advocated by some experimenters. The value of this measure is open to question. Studies by Winterberg and Wulfeck found that more targets were detected and more detail was resolved in complex scenes by additive color viewing than with natural color films; this was attributed primarily to enhanced chromaticity and brightness contrast of additive spectral records, effects opposite to de-saturation.

ILLUMINATION CONTROL

In additive viewing, illumination is controlled simply by varying lamp voltage. It is not necessary to go to the cost and complication of having a large series of neutral-density filters. The color temperature of the lamp changes but the spectral filter still continues to transmit light within its designed passband; only the amount of energy transmitted is changed, which would also occur with the neutral-density filters. Figure 6 shows radiometric measurements of the effects of large lamp voltage changes for two Wratten filters. Note that peak wavelengths and half-power points do not shift.

It is often specified that illumination must be controlled in a series of very small graduations, such as 5 percent, accurate to ± 5 percent. The cost of meeting such specifications is needlessly exhorbitant for normal viewing purposes. Response of the human eye and photographic materials tends to be logarithmic rather than linear. The relationship of percent transmission to optical density is plotted in Figure 7. At one end of the scale, the difference between 100 percent transmission and 95 percent ($\Delta D = 0.02$) is equivalent to putting a piece of plain glass in the optical path. More useful illumination step increments for both visual and photographic recording would be calibrated voltage settings which control illumination in the equivalents of one-half lens aperture stops; such as 100, 70, 50, 35 percent, and so forth, as in Figure 7.

IMAGE REGISTRATION

Excessively exacting precision for multiple-image registration is frequently said to be necessary for useful viewing and interpretation.

Multiple image registration should be accurate enough to avoid visible color fringing in an aerial photo image viewed at a normal distance. Under optimum conditions of illumination and contrast, the eye can resolve

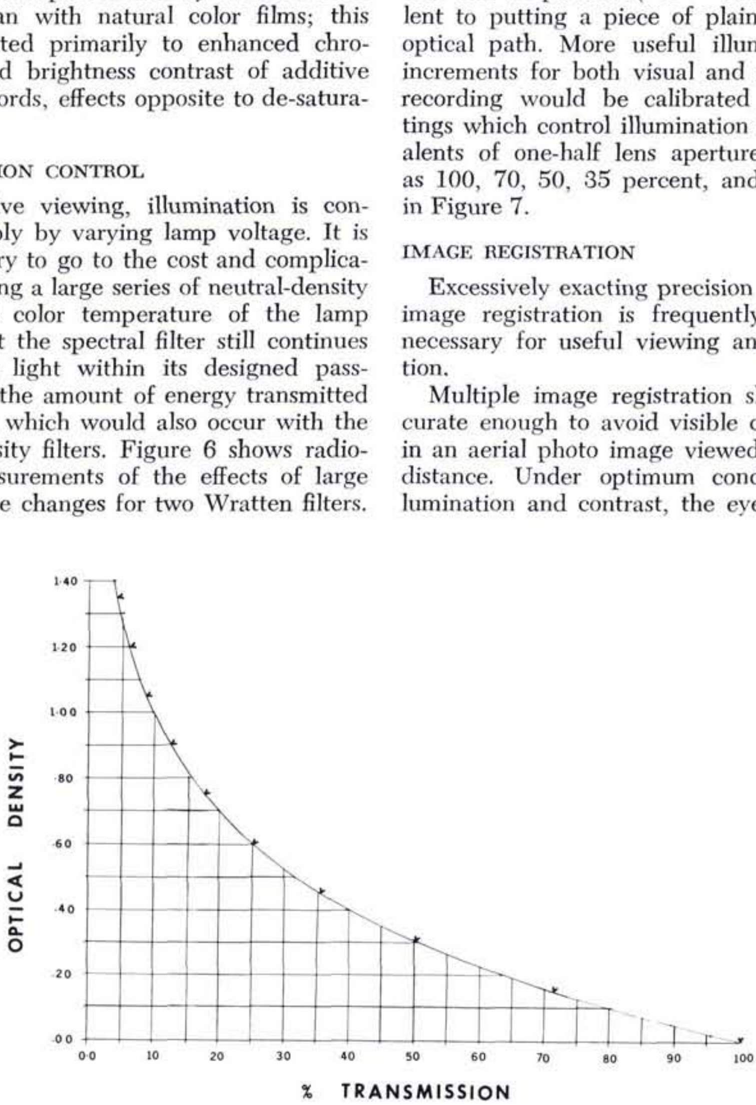


FIG. 7. Optical density versus percent transmission. The sensitivity of the eye tends to follow the curve. Points equivalent to one-half aperture stop differences are marked (**V**) for photographic exposure control purposes ($\Delta D - 0.15$).

about one arc-minute of subtended angle; but normal resolution is about 12 arc-minutes. One arc-minute is about 0.005 inch at 18 inches distance in a photograph. Seven to ten line/pairs/mm at 10 inches is also quoted; this is a target bar and space width of 0.004 inch. In a viewer of the type shown in Figure 2, the maximum image registration error on the screen is normally within ±0.0025 inch. With aerial photo images this is imperceptible and must be measured with high-contrast projected grid images.

As scale and rotation differences have been avoided in the camera, only small x, y image motions are needed for registration. Four spectral images of a scene can be registered in the viewer within 20 or 30 seconds, and as all images are on one roll of film, rapid scanning of many is possible during a short working period. Special registration marks are not needed, as the images provide a wealth of detail serving the purpose.

MULTISPECTRAL IMAGE INTERPRETATION

Rapid growth in the remote sensing field has introduced many to aerial and multispectral photography for the first time. Some have been led to expect the image information related to their specialties to be presented in clear, unmistakable form as the knobs are turned. Alas, there are few if any *unique, spectral signatures* in nature.

Multispectral photography and additive color display provide more powerful, flexible tools than we have had before, but as has always been the situation, the interpreter not only must have expertise in the subjects he is analyzing, but familiarity with their appearance in an aerial photograph. In the earth sciences, foresters, geologists and agronomists have been forerunners in photo interpretation. Much of their skill has been founded on relating personal knowledge of ground truth with its appearance in the aerial photograph. For a long time to come, the human and his stored experience are going to be part of the loop in translating image information into useful data. At least, the multispectral system enables the familiar color world to be re-created, into which unreal color hues and false balances can be introduced to enhance subject matter; but we all have a learning process ahead of us to exploit fully these techniques.

SUMMARY

Simplified production equipment is now available for multispectral photography and additive color display. Standardized results can be obtained for comparing results obtained among experimenters. High-quality imagery is provided for routine interpretation, research and training without adherence to excessively stringent, largely academic and costly specifications. The systems use black-and-white negative and positive films and conventional processing. Superior natural- and false-color effects not obtainable with color films are created and controlled by the user. The user is the final arbiter; but his success in converting image information into useful data still depends primarily on the depth of specialized subject knowledge he brings to the task. Multispectral systems uniquely aid his subjective judgement processes.

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Two Meetings in October—see pages 616 and 629.