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EKIT REPORT NO.4 FLIGHT NO.1

EVALUATION OF SO-121 AT LOW SOLAR ALTITUDES

16 NOVEMBER 1966

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1. SUMMARY

This report is number 4 in the EKIT series, and contains the evaluation of EKIT flight test no. 1. The purpose of this test was to evaluate the performance of Eastman Kodak Aerial Film Type SO-121 at low solar altitudes. SO-121 is an Ektachrome Type reversal color film that possesses resolving power capabilities higher than most color materials. As compared with black and white films, SO-121 is most nearly like Eastman Kodak Type 3400 (in terms of resolving power). The purpose of the EKIT flight test series is to investigate means for fully exploiting the flexibility (exposure control and filter selection) available with the improved KH-4b system.

SO-121 has been shown in past tests to be a potentially useful material for intelligence data gathering. Although the full usefulness of color film in a satellite vehicle has not been established, its use is promising enough to warrant continued investigation as to its implementation with the KH-4b system. A limited amount of SO-121 has been flown with a high altitude aircraft at normal solar altitudes. The results of these tests have been quite encouraging, producing high quality color photography. The performance of SO-121 at low solar altitudes, however, has not been investigated. Because of the nature of satellite photography, it is obviously necessary to consider how SO-121 would perform under low solar altitude conditions if such a material is to be used in the KH-4b system. Hence, the main goal of this test was to evaluate the performance of SO-121 at low solar altitudes, and to predict what its performance would be under these conditions with the KH-4b camera system.

1.1 SCOPE OF THE TEST

The SO-121 used in this test was gathered by a high altitude aircraft flown on 28 July 1966. The nominal altitude was 65,000 feet. The 112B camera system was used. Both forward and aft cameras were loaded with SO-121. A constant exposure slit was employed on both cameras; however, a 0.35 ND filter was placed over the forward camera slit. This was done so that the forward camera would provide nominally correct exposure at 20 degrees solar altitude, and the aft camera at 15 degrees solar altitude. In this fashion, a maximum range of properly exposed, underexposed, and overexposed material resulted. The flight line was constructed to allow maximum replicate coverage of Bakersfield, California, for comparative purposes. CORN targets were deployed at Bakersfield and were covered on nearly all passes. The first pass started at 5:33 a.m. (5.2 degrees solar altitude) local time and the last pass concluded at 8:13 a.m. (37.3 degrees solar altitude) local time. The weather was excellent, and the haze conditions were "nominal." The analysis of this test material is basically divided into three areas: (1) reproduction analysis, (2) subjective analysis, and (3) KH-4b system considerations.

The purpose of the reproduction analysis is to evaluate the tone and color reproduction characteristics of SO-121 under the conditions of the test. This kind of analysis becomes a bit more difficult with color materials. With black and white films (under similar conditions), one really only has to concern himself with exposure, that is, proper placement of the scene luminance on the D-log E curve of the film. With color films, however, the problem is a bit more complex. Not only is exposure (on the D-log E curve) important, but the rendition of colors is equally important, for color film can be properly exposed (from a D-log E point of view) and yield poor color reproduction. Therefore, our analysis evaluates the effect on both exposure and color reproduction of low solar altitudes. As will be seen, this analysis can be used to good advantage to specify not only what kind of exposure corrections are required, but also what kind of color corrections are required to produce the best color material possible under the circumstances.

The purpose of the subjective analysis is to give an initial indication of the photointerpreter usability of SO-121 at various solar altitudes, for the conditions of this test. It should be made clear that we have not attempted to comment on the general usefulness of color photography, for this was not the purpose of the test. However, comments by a trained photointerpreter are included to indicate the relative kinds of information available (or lost) as a function of solar altitude with the SO-121.

The KH-4b system analysis applies the test results directly to the KH-4b system. It is our purpose here to indicate, as a result of this test, what the impact of SO-121 in the KH-4b camera will be. The resolution attainable, the tradeoffs that must be considered, and our exposure recommendations are included as part of this analysis. Whereas in the past, all predictions on SO-121 in the KH-4b camera have been theoretical, the data presented herein are practical and should be considered as our latest recommendations. Perhaps of greatest interest is the new recommendation on slit sizes, and changes to be used in flight, with KH-4b and a full load of SO-121, as a function of solar altitude.

It should be emphasized that the results of this test, strictly speaking, should only be considered truly valid with the particular emulsion batch of SO-121 employed. The film manufacturer has to work to tolerance levels, and there is no guarantee that successive batches of any film (particularly color films) will be identical to previous batches. However, assuming that the manufacturer makes no major changes in the characteristics of SO-121, the results herein can be considered generally applicable.

1.2 CONCLUSIONS

As a result of this test and the evaluations conducted, several conclusions are possible. These conclusions are summarized below.

1. SO-121 can be generally employed at solar altitudes as low as 10 degrees. For certain kinds of information, SO-121 can be used at lower solar altitudes.
2. In the KH-4b system a full load of SO-121 could be properly exposed (by slit control) to solar altitudes as low as approximately 13 degrees. Exposures at 10 degrees solar altitude would be quite acceptable.
3. The maximum resolution that could be expected with SO-121 in the KH-4b camera (assuming current lens and correct exposure) would be approximately 60 lines per millimeter.
4. Color reproduction is poor at very low solar altitudes when using the nominal color correcting pack. A separate color correction pack should be considered for these cases. This is practical for a full color mission, and impractical with a split load of black and white and color.

2. TEST PLAN

EKIT test no. 1 was flown on 28 July 1966. It was flown with the high altitude aircraft using the 112B camera configuration. This section discusses the 112B camera and the flight test details.

2.1 112B CAMERA

A brief description of the 112B camera is warranted to introduce the system used in this EKIT test. The camera, a pan scanning type, has been designed around a diffraction-limited Petzval type lens of 24-inch focal length, with an f/3.5 aperture that covers a 6-degree field angle. To obtain stereo, a pair of these cameras is tilted from the nadir at 13 degrees each, and set face to face so that each camera scans in opposing directions. The lens is continuously rotated about its operational nodal point and scans across the line of flight and is translated against the flight direction for image motion compensation.

During approximately 70 degrees of the lens rotation, a capping shutter is opened to permit the aerial image to expose the 70-millimeter film through a slit. This slit controls the exposure time, e.g., at a 20-inch per second scan rate, a 0.040-inch slit produces an effective exposure of 1/500 second. At the completion of the photographic scan, the capping shutter is closed.

The film is continuously being transported in from the supply spool and out to the takeup spool. A frame-metering roller controls the frame length, the correct amount of film is placed in the format area, and clamps at each end of the format hold the film stable and in the approximate focus position. The excess film is accounted for by a shuttle assembly that gives or takes according to demand.

The focal position is determined by a scan head assembly mounted on a precise arm from the nodal point to the focus. This scan head gently lifts the film from the rails to the image plane during exposure and returns it to the rails after exposure. The rails are required only to hold the film at the approximate focus and to guide film during transport.

Recorded on the film edge outside of the format area on each frame are frame number, binary time, and timing pips of 125 cycles per second. These timing pips are scanned on the film across the 70-degree format length with one pip blanked out to indicate when the binary time data block is printing out. Three scanning rates are built in to match the V/h requirements while maintaining approximately 10 percent overlap at the format center. Increased overlap is acquired on both sides of nadir as the off vertical scan angle increases.

The exposure slit and filter are preselected for the V/h requirement and subject illumination and consistently produce the correct exposure.

A major consideration of all EKIT testing is that no modification be made that was not compatible with the normal system operation. The camera is therefore not changed in any mechanical sense. Other restrictions placed on the test series were: (1) that exposure times be short enough to prevent any vehicle disturbance to the image and (2) that the exposure slits remain sufficiently wide to prevent any diffraction effects.

Where film characteristics require settings exceeding the above restrictions, specially designed and fabricated filters or exposure slits were used, e.g., Inconel coating to reduce transmission with no loss of quality, step-type exposure slits to give half of each format width a different exposure, and split filter to give two filter conditions to one format.

2.2 FLIGHT TEST PLAN

EKIT test flight no. 1 was flown on 28 July 1966. The flight number is [redacted] Both cameras were used and were loaded as follows:

	Master Unit (I5) Aft-Looking	Slave Unit (I6) Forward-Looking
Film	SO-121	SO-121
Slit width	0.031 inch	0.031 inch
Exposure time	1/600 second	1/600 second
Color correction filter	CC30B	CC30B
Haze filter	W-2E	W-2E
Neutral density filter	None	0.35
Scan mode	II	II

A 0.9 ND filter was placed over the frequency markers and frame counter on both cameras.

The flight lines consisted of replicate passes, at approximately every 25 minutes over Bakersfield, California. The flight lines are shown in Fig. 2-1.

Fig. 2-1 — Flight lines for Bakersfield, California

3. REPRODUCTION ANALYSIS

As mentioned in the summary, two separate evaluations were performed on the reproduction capabilities of SO-121 at low solar altitudes: a tone reproduction and a color reproduction analysis. The tone reproduction specifies the system's capability to reproduce a scale of gray (neutral) tones. In the case of color materials, these tone reproduction capabilities are described by the three (cyan, magenta, and yellow) END* versus log E (or log reflectance) curves. The END curves for the three layers in the color film completely specify the ability (or lack thereof) of the color system to reproduce neutrals. Hence, three identical END curves indicate a perfect visual reproduction of neutrals. Departure of the END curves from equality indicates the departure from neutrality. The END curves are, therefore, an excellent measure of the system's ability to reproduce neutrals as neutrals, a basic tenet of color theory.

The color reproduction analysis has been done to illustrate both the range of colors that can be reproduced (color gamut), and the shift in color reproduction with changes in solar altitude. With color photography, changing solar altitude has a more complicated effect than that encountered with normal black and white reconnaissance. In the black and white case, lowering solar altitude causes primarily only a decrease in apparent contrast, that is, as solar altitude decreases, the ratio of hazelight to direct illumination increases causing a lowering in the apparent contrast. With color, this effect also occurs. In addition, however, there is an important shift in the color temperature of the illumination which will, of course, affect the color balance of the final color record.

The result of the shift in color can be best illustrated on the CIE chromaticity diagram. This diagram allows one to graphically illustrate the changes in color reproduction as they relate to the human observer, for the CIE chromaticity system is related fundamentally to the "standard observer." It is therefore possible with the CIE system to show both the gamut of color reproduction possible, and how color reproduction has shifted for various conditions. Both of these analyses are discussed below.

3.1 TONE REPRODUCTION

The CORN target array at Bakersfield consisted of an edge, a resolution target (T-bar), color patches, and a 5-step gray scale. Each successive pass over the Bakersfield area, therefore, had an image of the gray scale. This gray scale was used in the tone reproduction analysis. In normal black and white photography, the tone reproduction analysis would be performed by measuring the density on the film (that resulted from each step on the gray scale) and plotting these densities versus the log reflectance of the gray scale (in effect a D-log E curve). The

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* Equivalent Neutral Density. For those not familiar with color densitometry Appendix A gives a brief summary of the terms and their definitions.

analysis of color is, however, more complex since there are three separate records of the gray scale in the color emulsion, i.e., a blue, a green, and a red record. That is, the color film in fact contains three images of the gray scale, each corresponding to a different portion of the spectrum. This means, then, that the sensitometric characteristics of each individual record must be evaluated if the reproduction is anything but neutral which is the case with this photography.

Appendix A should make it clear why the tone reproduction analysis must be done with END's and not with the normal arbitrary red, green, and blue densities. Fundamentally, the problem is that color film dyes are not perfect. That is, the cyan dye, which controls the red light, also absorbs smaller amounts of blue and green light. This is also true with both the magenta and yellow dyes. It is necessary, therefore, to use densitometric techniques which measure the effect due only to each individual layer independent from the other two. END is such a measure.

Since END is a quantitative specification of the departure from neutrality, the END versus log reflectance curves measured (from the CORN targets) can be used in a normal tone reproduction sense to analyze the source of the non-neutrality, such as the atmosphere.

The tone reproduction analysis was performed by measuring the red, green, and blue integral spectral densities (ISD) of the image of the CORN gray scale for each solar altitude. Since the steps were small, a microdensitometer was used that was cross-calibrated for ISD's with a diffuse densitometer. The resulting ISD's were converted to END's and plotted as shown in Figs. 3-1 and 3-2 for the forward and aft camera imagery.

Figs. 3-1 and 3-2 are the plots of END versus log reflectance (for the gray scale) for each camera at seven solar altitudes. The increase in exposure, with increasing solar altitude, is readily apparent, in the figures, as a gradual lowering of density. The effect of the forward camera's reduced exposure level can be seen in that its END curves are all at a high level vis a vis the aft camera curves. For both cameras, at all solar altitudes, the cyan END is greater than that of the magenta or yellow. This indicates that the gray scales (and hence the pictures) should look cyanish. This is, in fact, the visual appearance of most of the photography.

Fig. 3-3 illustrates the entire tone reproduction plot for the best exposures from both cameras. Quadrant IV of this figure is the final reproduction of the CORN gray scale. These are measured values from the images. Quadrant III is the color sensitometry (END versus log E) for SO-121. These data are measured from a laboratory-prepared sensitometric strip and represent the best rendition of a neutral wedge possible (under the test conditions). It is, therefore, the best possible relationship for neutral representations between the dye layers. Quadrant II is the transfer quadrant from the log exposure axis of Quadrant III to the effective exposure axis of Quadrant I. Quadrant I, then, represents the effects of the atmosphere (and lens) on each of the three light sensitive layers in the color film.

This data is generated by passing the density values of Quadrant IV through the color END log E curves and out to the log exposure axis. When the generated log exposures are plotted versus the original target log reflectances, the effect of the atmosphere has been found.

Note that with both cameras the blue contrast is very low, the red contrast is highest, and the green in the middle. This is as expected. Although these tone reproductions are for the best exposures, it is interesting to note that they are not equal. This is significant, in that it graphically illustrates that equal exposures, at different solar altitudes, will not produce equal pictures. In this case the aft camera reproduced images with less saturation and lower contrast. This situation is easily explainable since the aft camera did not have any ND filter on the slit. This means

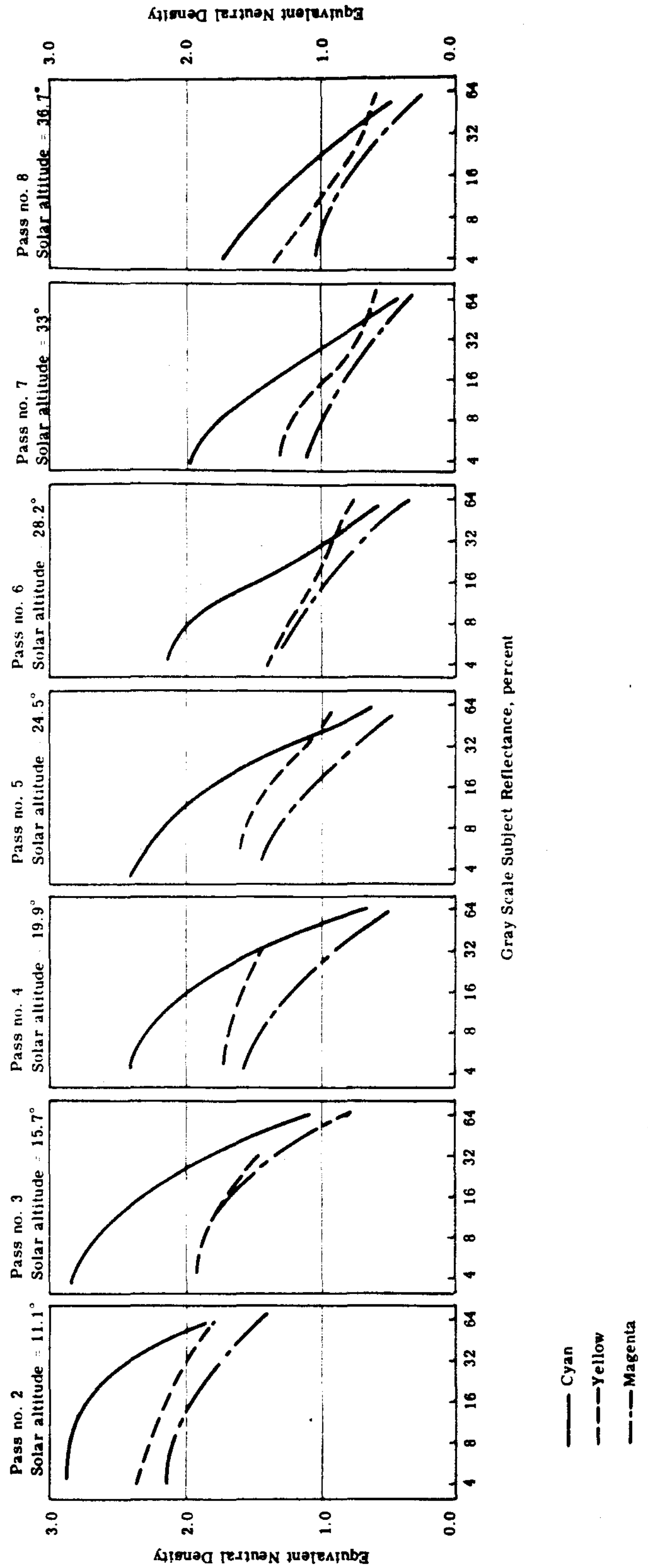

Fig. 3-1 — Equivalent neutral density versus gray scale (log) reflectance for the forward camera at various solar altitudes

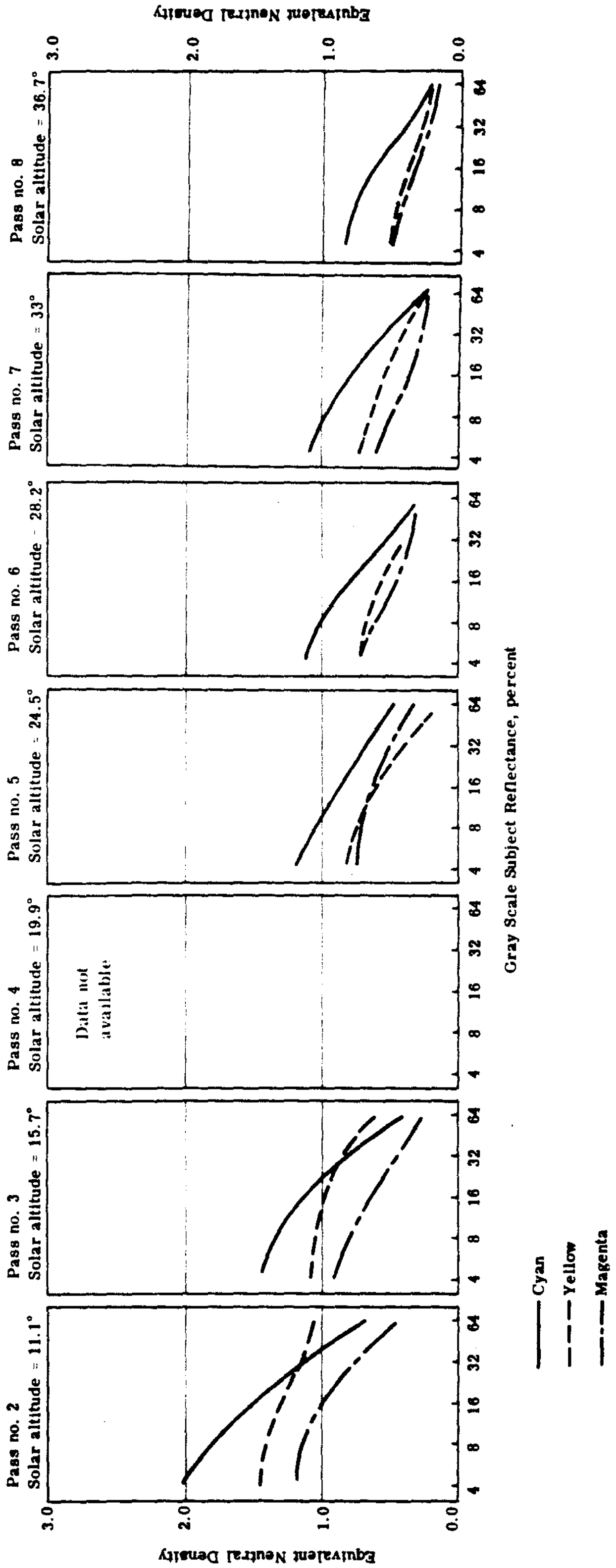

Fig. 3-2 — Equivalent neutral density versus gray scale (log) reflectance for the aft camera at various solar altitudes

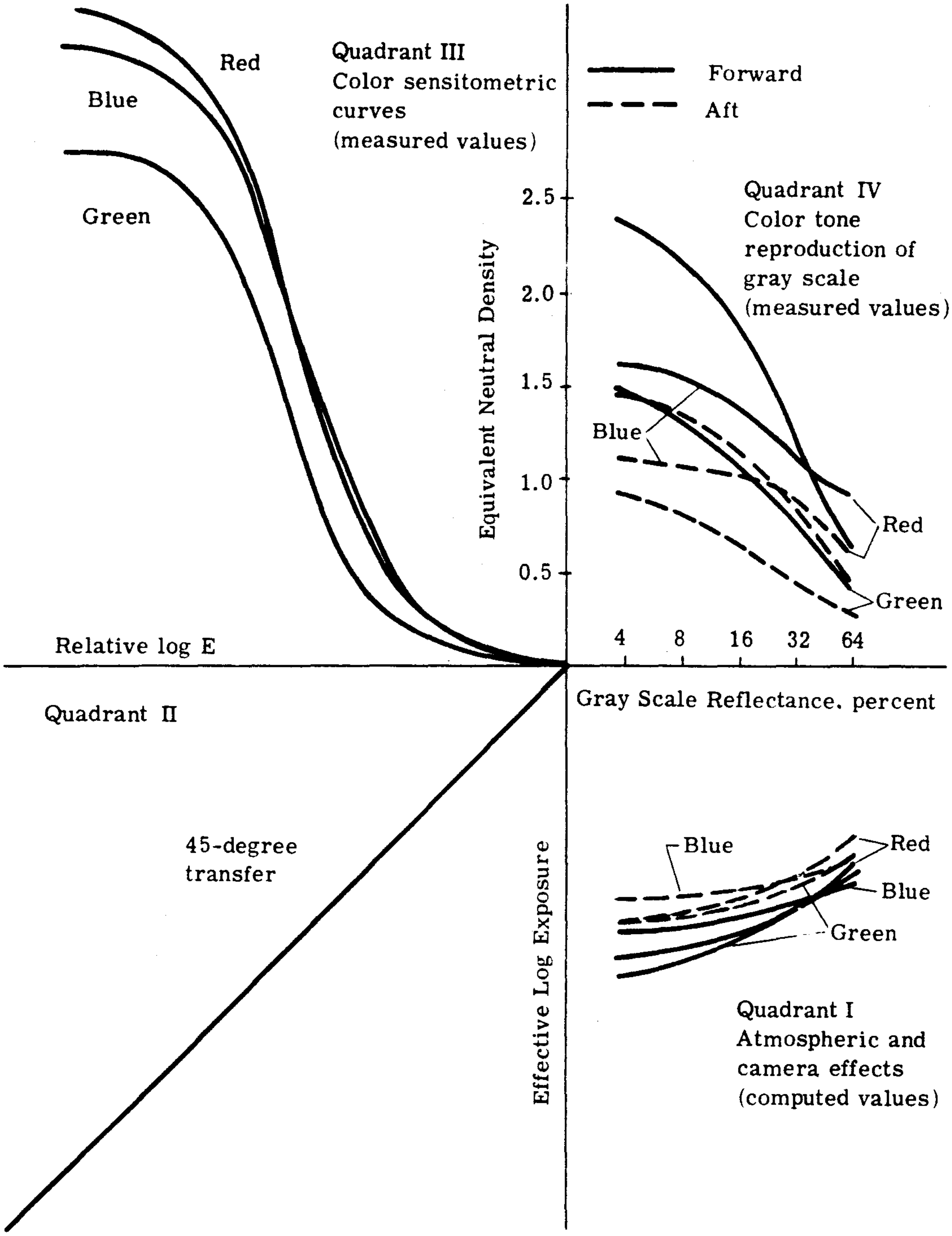

Fig. 3-3 — Tone reproduction for the best pictures that the best aft exposure runs at a lower solar altitude than the forward camera exposure which had a 0.35 ND filter over the slit. Lower contrast and color saturation can be expected at lower solar altitudes due to the increasing amount of atmospheric haze and its subsequent effect on the imagery.

This tone reproduction analysis was performed on all passes for both cameras. The contrast between the second and fourth steps of the gray scale was 4:1, a log value of 0.6. The effective contrast for each sensitive layer between these steps was measured. Since the tone reproduction plot allows elimination of the effect of gamma on contrast determination, it is possible to measure the "apparent contrast," that is, it is possible to determine the apparent contrast of the two gray scale steps as presented in the focal plane. It is, therefore, possible to calculate the apparent blue, green, and red contrast of these two steps on the gray scale in the focal plane.

Fig. 3-4 shows the results of these determinations. Here the low contrast of the blue aerial image can be seen in comparison with the red and green. There is, as expected, an increase in contrast as solar altitude increases. However, the blue contrast, even at its maximum, never reaches even the minimum of the green and red contrast. From this analysis, it can be concluded that the blue record is contributing relatively little to the image due to the lack of contrast. This conclusion implies that a heavier haze-attenuating filter, such as a Wratten no. 4, would probably have produced better results. The use of a Wratten no. 4 filter would not only allow greater attenuation of the atmospheric haze, but would reduce slightly the contribution of the blue layer to the image. This should produce more nearly correct color photography.

From this analysis it is obvious that the color correction filters used (i.e., Wratten no. CC30B) are not optimum for low solar altitude work. The illumination and haze spectral conditions are different enough from the normal (i.e., over 30 degrees solar altitude) condition that changes in color balance occur. The tone reproduction analysis discussed above was used to obtain an estimate of the CC filters that would be required to form a neutral scale of grays. The procedure was to use the tone reproduction graphs in Fig. 3-5 as a standard and work backwards from this with various color correction filters. The graphs shown are a direct computer plot obtained with an on-line digital plotter associated with the CDC-924 computer. This capability allows us the flexibility of changing various color system parameters (such as CC filters) and allows us to see the effect on the final results.

The analysis consisted first of determining the effects of the atmosphere with the camera system as it was when the imagery was made. This is shown in Quadrant I in Fig. 3-5, and was obtained as previously described. When a new CC filter (or filters) was chosen on the computer for test, its effective filter factor for each layer, with respect to its spectral sensitivities, was determined. This value was added to each of the curves in the atmospheric Quadrant I. The resulting curves were projected through the three color sensitometric curves to produce the resultant, theoretical color reproduction. That is, this technique allows us to predict (with a given atmosphere) what the reproduction of grays will be on the camera film. Fig. 3-6 illustrates the experiments so run on the computer. These curves are a series of END versus log reflection (of a gray scale) curves for different color correction filter combinations. This is a trial and error process but it must be remembered that our goal is to produce three identical red, green, and blue END curves, for this is the only case where neutrals will be reproduced as neutrals.

The sequence of events in Fig. 3-6 is as follows. From the initial condition (Block 1, corresponding to Quadrant IV of Fig. 3-5), a correction was made for the CC30B filter used in the camera at the time of photography. Block 2 illustrates what would have happened without the

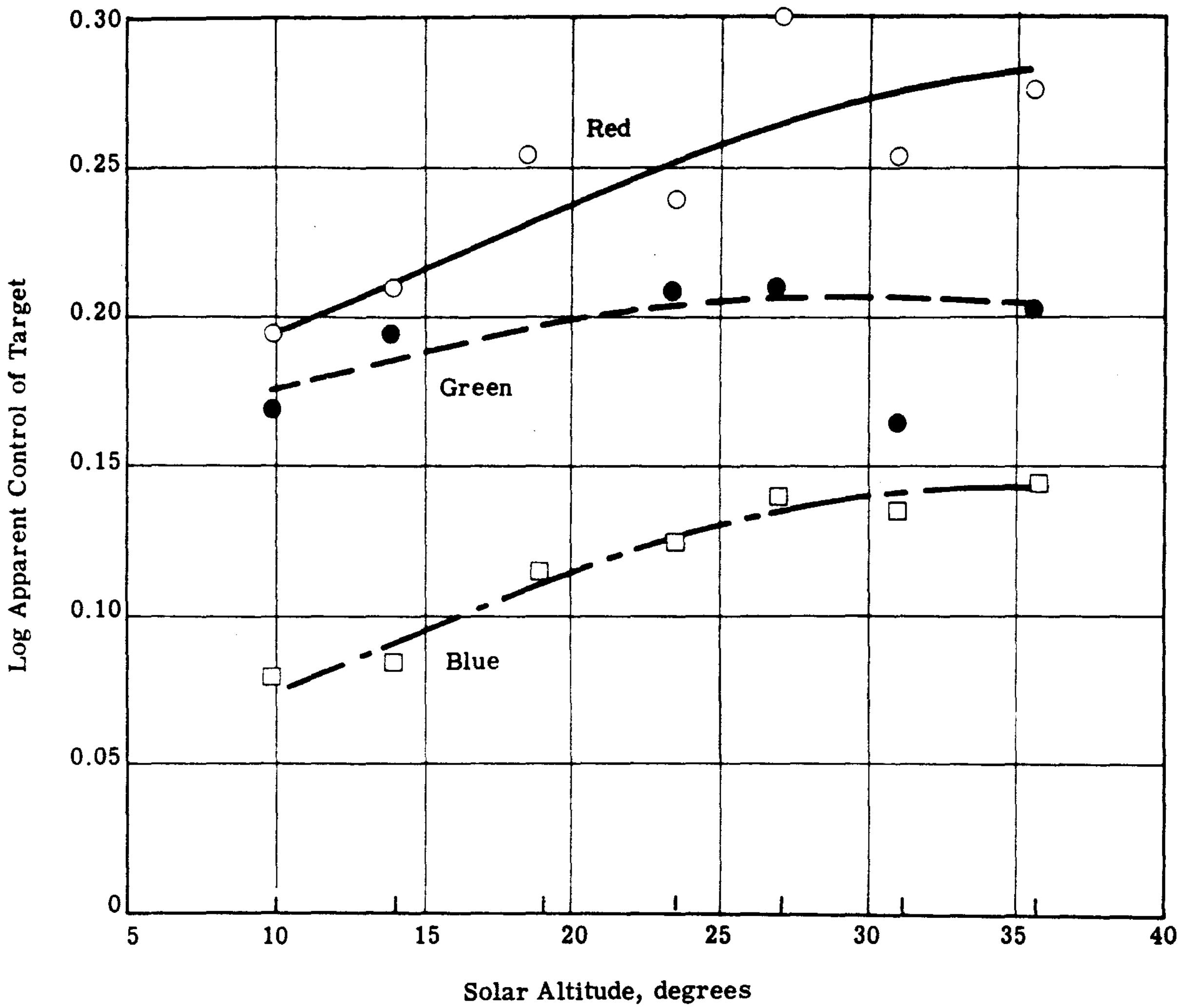

Fig. 3-4 — Apparent red, green, and blue contrast of steps 2 and 4 of gray scale (log contrast on ground = 0.6)

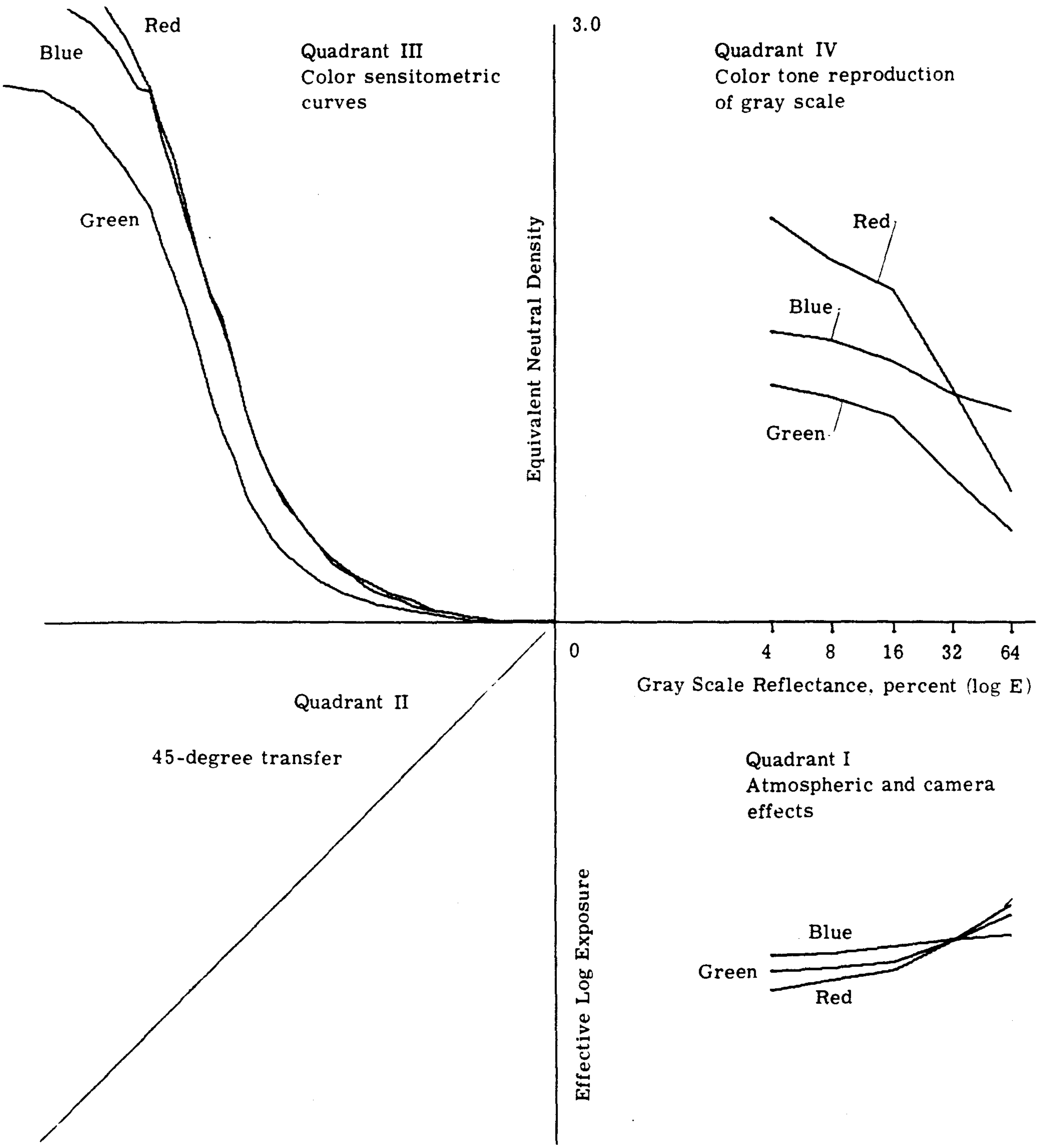

Fig. 3-5 — Color tone reproduction for aft camera at 11-degree solar altitude

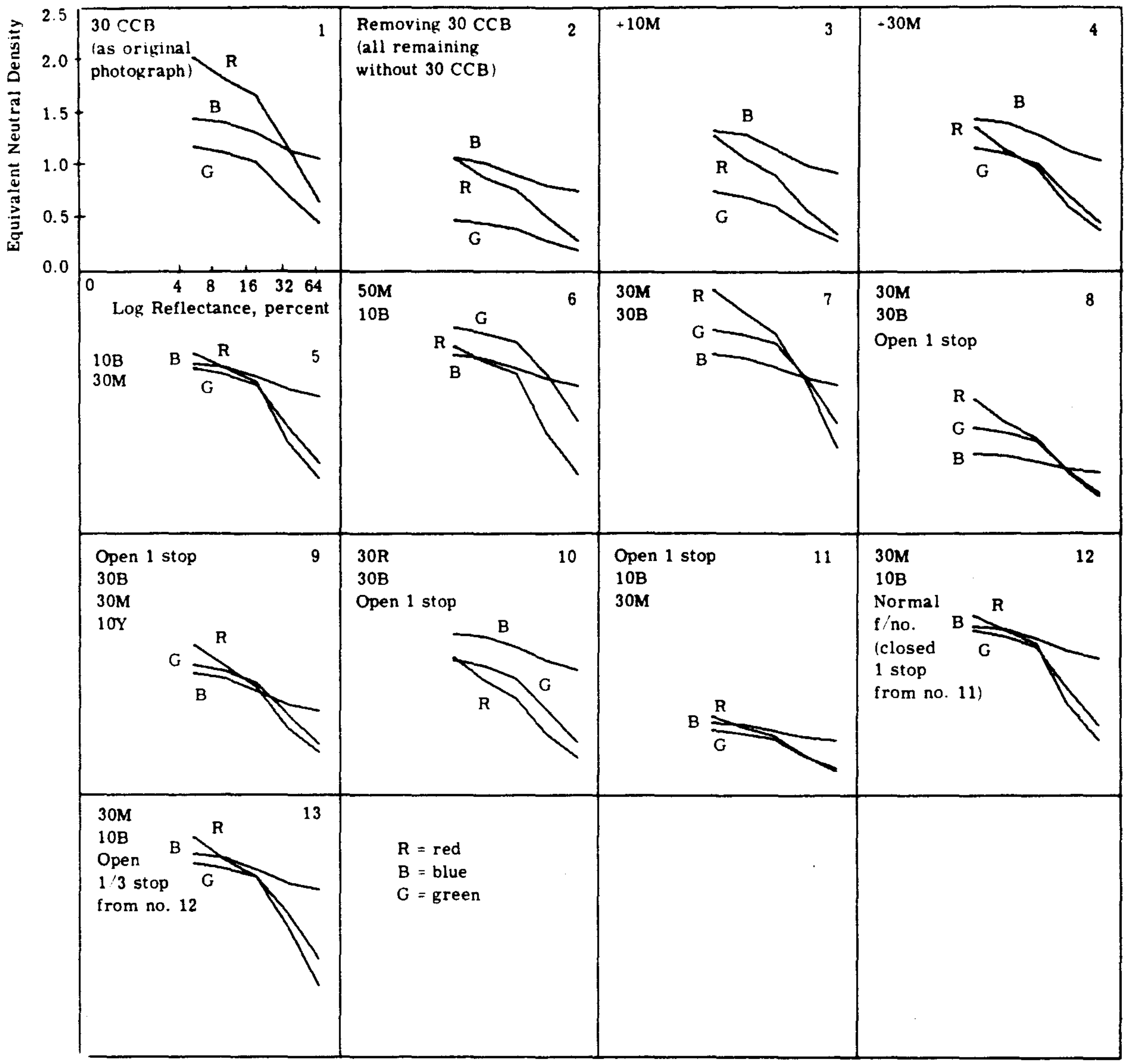

Fig. 3-6 — Fourth quadrant tone reproduction graphs computed for various CC corrections

CC30B filter. The result indicates low densities due to the resultant overexposure. This block (2) was now considered as our control condition as it has no CC filtration. The purpose now is to add CC filtration until the three curves are as equal as possible.

The green curve in Block 2 was very low; a correction was made to raise it by adding a CC10M filter. This improved the green (Block 3) but not enough, so a CC30M was added (Block 4). At this point, the green and red were fairly well matched but the blue was too high. A CC10Y was added to the CC30M to lower the blue record (Block 5). This improved the results considerably in the shadow regions though the blue contrast was so low that the highlights were out of color balance.

Unfortunately the blue contrast problem cannot be improved with the CC filters since this is a function of the atmospheric conditions of the day. Further attempts were made to improve the results. Block 6 shows the addition of a CC50M plus a CC10B. This raised the green, but generally degraded the color balance. A CC30M plus a CC30B (Block 7) produced a very heavy image. To compensate for this, the exposure was increased by one stop (Block 8). Neither of these attempts produced any significant improvement. However, the further addition of a CC10Y to this (Block 9) did give a somewhat better color reproduction over the average of the five gray steps. In Block 10, a CC30R plus a CC30B was substituted for the CC30M plus CC10Y (still with one stop more exposure). This substitution also did not improve the results. A CC10B plus a CC30M combination (Block 11) was overexposed. This same filter combination (Block 12) with the f/no. brought back down to normal produced the same results as Block 5. A final test of this same filter combination (CC30M plus CC10B) with 1/3 stop additional exposure produced the best results as indicated in Block 13.

The conclusion from this exercise is that for solar altitudes on the order of 11 degrees, a CC10B plus CC30M or a CC30B plus CC30M plus CC10Y filter pack will give better reproduction of neutrals. The former filter pack would work best with about 1/3 stop overexposure and the latter with about 1 stop more exposure relative to that given with the normal CC30B filter used. The inability to obtain a "perfect" rendition of neutrals is hindered by the blue contribution of the atmosphere.

3.2 COLOR REPRODUCTION

The CORN target array included a red and blue patch that was used in the color reproduction study. The visual appearance of an object is a function not only of the object itself, but the illumination that is used to view it. Since the photographs were taken under varying illumination conditions, there is no single CIE coordinate for the CORN red or blue patches. An estimate has been made of the illumination reaching the ground during the early passes over the target area. This estimate was used to compute the CIE coordinates of the red and blue patches as indicated in Fig. 3-7. The CIE values of the color patches were determined for the second through the eighth passes (11 to 37 degrees solar altitude).

A trend in these data of increasing reddishness to the images as the solar altitude increased might have been expected. This was not the case for these targets. The values for each patch were randomly scattered within a small region that is indicated in the insert of Fig. 3-7. An explanation for this is that these targets were so saturated that they, in effect, looked the same to the film under the various illumination conditions. The image of the red patch is considerably closer to the illuminant, 4000 °K, than that of the blue patch. Visually, though, it appears quite red. This apparent contradiction is introduced by the visual process. Since the background is

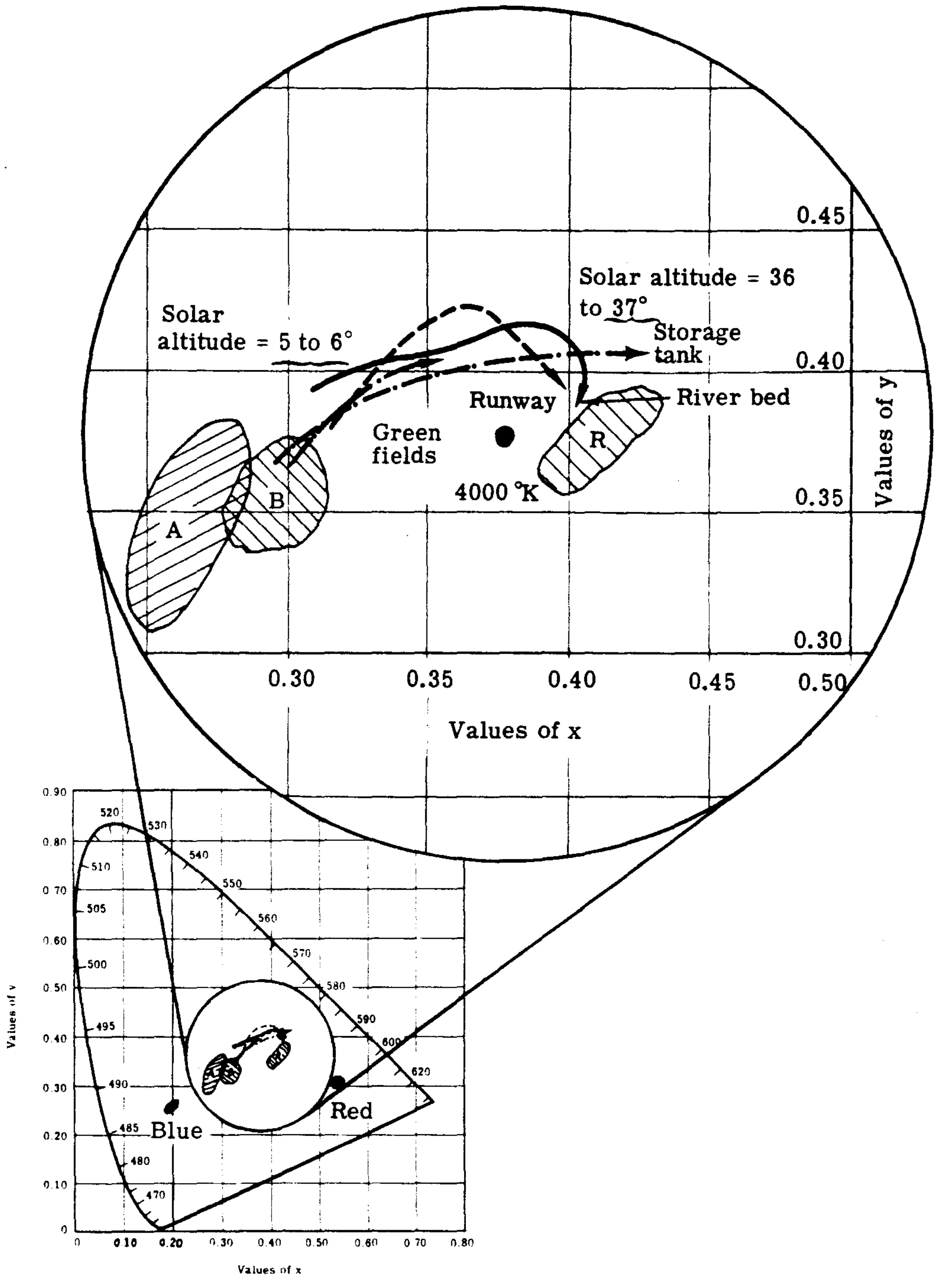

Fig. 3-7 — CIE coordinates of selected images. Arrows indicate the change in color reproduction from the lowest solar altitude (left) to highest solar altitude (right, arrowhead). Region A is from the frame with initial slow start-up exposure. Regions B and R are the reproduction of the blue and red CORN patches predominantly cool colored, the red patch stands out much more vividly than it would against a neutral or warm-toned background. In order to obtain a better representation of the change in color reproduction with solar altitude, several naturally occurring targets were chosen for a similar analysis. They were: (1) a green farm area, (2) a gray or brownish storage tank, (3) an airport runway, and (4) a river bed. These areas were all large enough to allow macrodensitometry and thus avoid any errors that might be introduced by a microdensitometer. The insert in Fig. 3-7 illustrates the change in color reproduction as a function of solar altitude. In all cases the color of the images are cyanish-green at 11 degrees solar altitude and become more green, then greenish-yellow, with some objects quite yellow. The green farm area, though, goes only as far as the green region. It should be noted at this point that only very small differences in the CIE values of objects are required for distinct color differentiation. This is particularly true of larger objects that have other identifying characteristics, i.e., shape, shadows, neighboring objects. The combination of shape and hue can work together for good identification. At the beginning of the first pass (5 degrees solar altitude), an interesting photograph was obtained. The camera scan arm was not up to its normal velocity and produced a 4× overexposure error on the first frame. The subject in this image was a residential area in a valley. This area was completely in shadow and illuminated entirely by skylight. A photomicrograph of a portion of this area is shown in Fig. 3-8.

CIE coordinates of several areas in Fig. 3-8 were determined. They all fall within the oval area A of Fig. 3-7. Though there may have been isolated instances of colors outside this region on the CIE plot (i.e., red in yellow cars), the overall color range is quite restricted. Even so, there is a considerable amount of information available. This is quite similar to black and white photography for this condition, with the added dimension of hue, even restricted as it is in range.

The color gamut of a system is the maximum range of hues that can be reproduced under a given set of conditions. Since the gamut is a function of the entire system, any component of the system can have a significant influence. The color gamut ties the tone reproduction of the system to the CIE diagram. In this computation, it is assumed that any colored object's maximum spectral reflectance is equal to or less than that of the white step of the gray scale. It is also assumed the darkest spectral portion of the colored objects in the scene is no darker than the black step of the gray scale. If this is true, and it is a fair assumption, then all colored objects will be reproduced with equivalent neutral densities between the extreme of the END's of the gray scale. Exactly where the three END values of color in general will fall is an unknown; however, this knowledge is not necessary when determining the system's color gamut. The gamut is determined by finding the CIE coordinates for all combinations of the END's that result from the 5-step gray scale. The locus of maximum reproduced hues, therefore, is the color gamut. Since the tone reproduction characteristics are different for each camera and each solar altitude, the gamuts also vary.

Fig. 3-9 shows the color gamuts for the forward and aft cameras at a solar altitude of 11 degrees. Both have similar shapes although that of the forward camera is at a darker luminosity level since it had less exposure. Both gamuts of Fig. 3-9 are quite large and thus the systems have the capability of reproducing a wide range of colors present in the scene. Very bright colored objects, such as school busses, red cars, and swimming pools would be reproduced fairly close to the extreme ranges of the gamut.

Fig. 3-10 shows the gamut of colors possible for both cameras at a solar altitude of 37 degrees. These gamuts are considerably different, the aft gamut being much more restricted. This difference is caused by the fact that the film was severely overexposed and the image, hence, "washed-out."

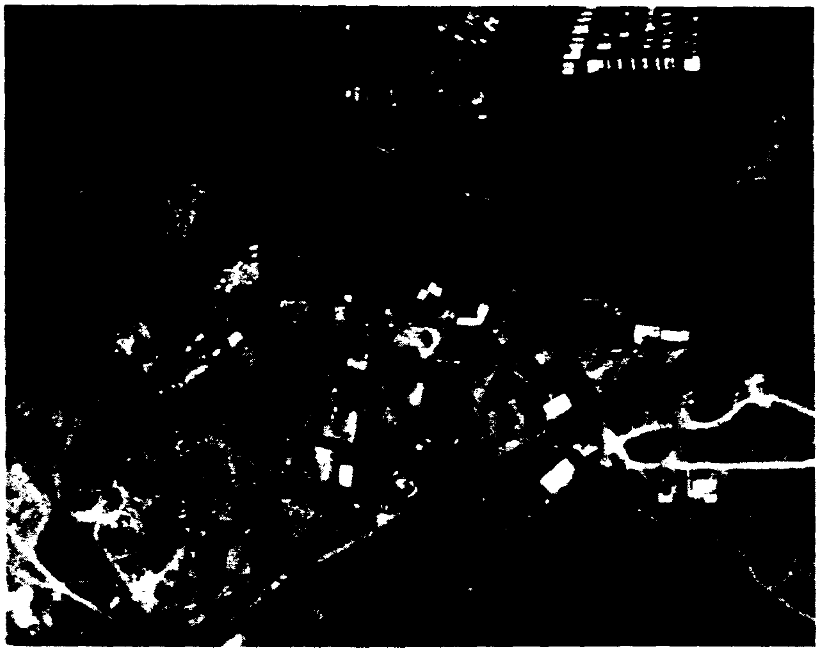

Fig. 3-8 — Cultural area in valley at 5 degrees solar altitude with no direct sunlight area in complete shadow; the only illumination is skylight. Good exposure is due to slow scan velocity which produced 4× increase in exposure over that normally obtainable.

NOTE: Extra prints of the scene were not available and consequently a half-tone was necessary. Though the color in the original was very poor, the half-tone does show that, given sufficient exposure, spatial information is present.

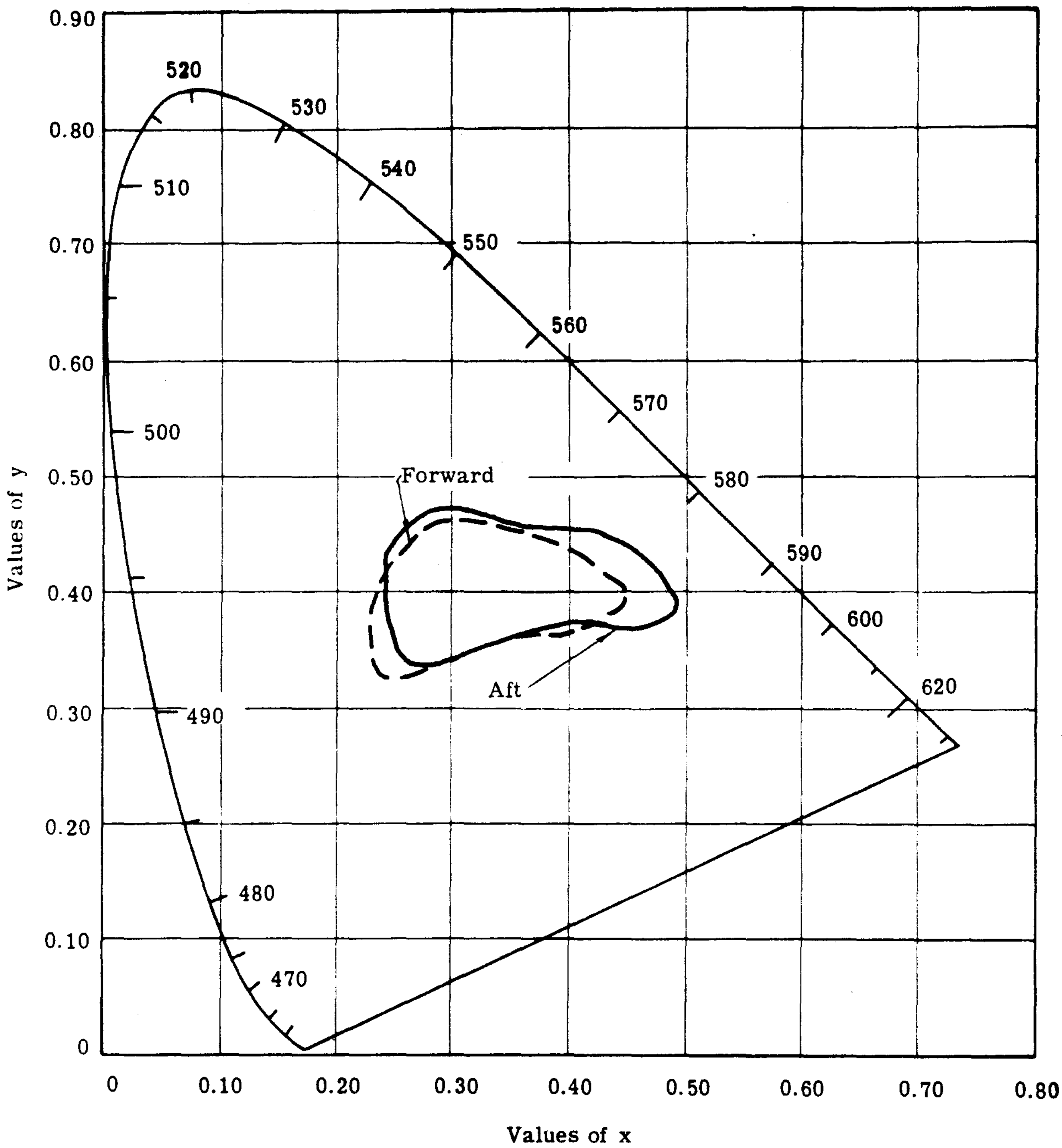

Fig. 3-9 — System gamut of colors for 11-degree solar altitude

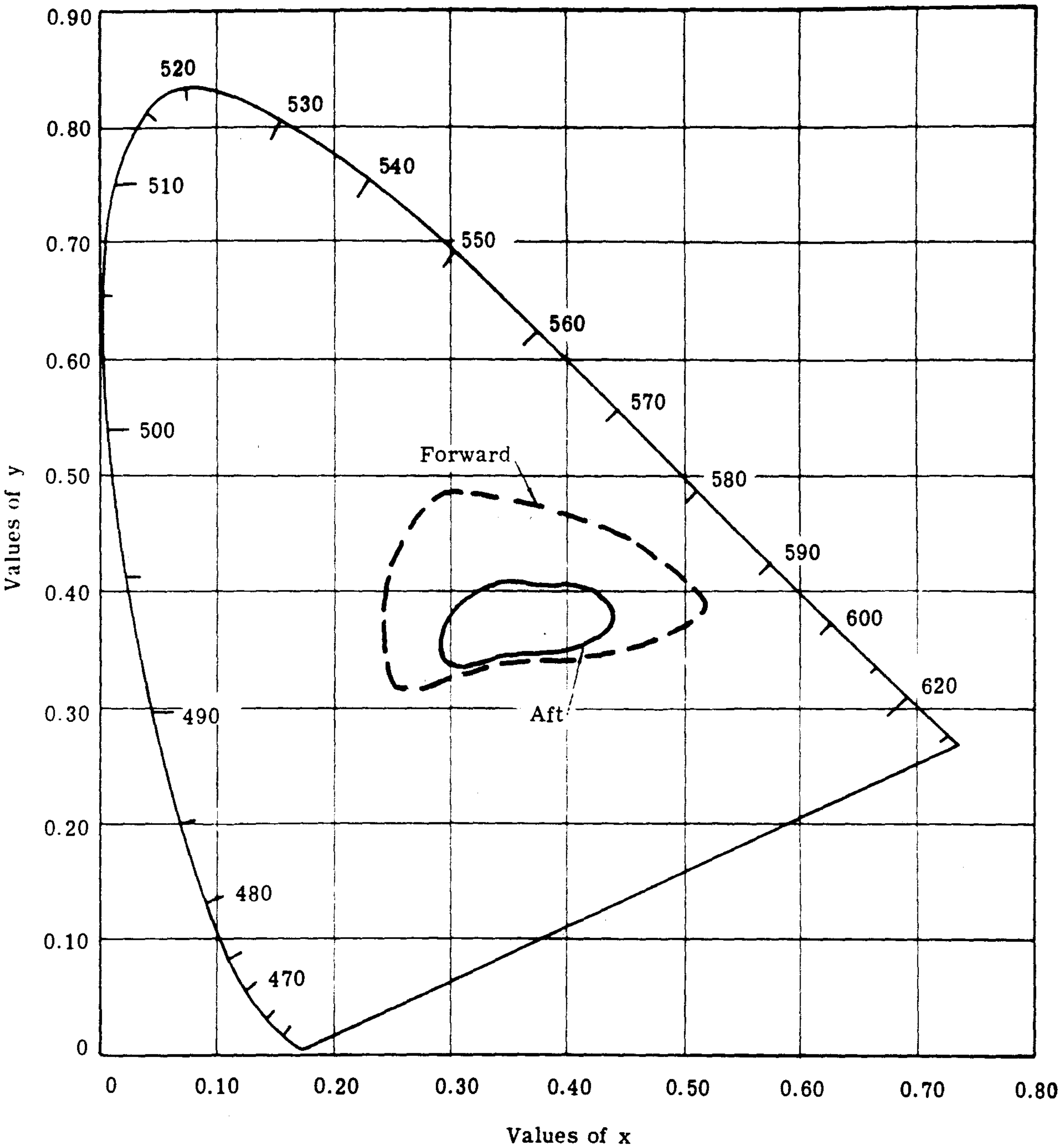

Fig. 3-10 — System gamut of colors for 37-degree solar altitude

The final gamuts, Fig. 3-11, are for the best exposure with each camera. Since the exposures were different for each camera, the best exposures occurred at different solar altitudes, hence the difference in color reproduction capability. The gamut of colors available is greater with the forward camera since the tone reproduction characteristics for the cameras are different due to the differences in solar altitude and exposure level. The forward camera's image has a greater tonal range than that of the aft camera, even though the best picture as far as resolution is concerned was obtained from the aft camera.

The color gamut alone should not be used as a measure of a system's capabilities for color reproduction. It is, however, a tool that can be used to measure the capabilities of the system to record colors of varying degrees of saturation and hue if they are present on the scene.

It is concluded from this analysis that the range of colors that could be reproduced is quite large even at 11 degrees solar altitude. The colors are darker, though, since they were generally underexposed at this solar altitude. With proper exposure the gamut of colors may be larger or smaller. In either case the range would still be quite wide.

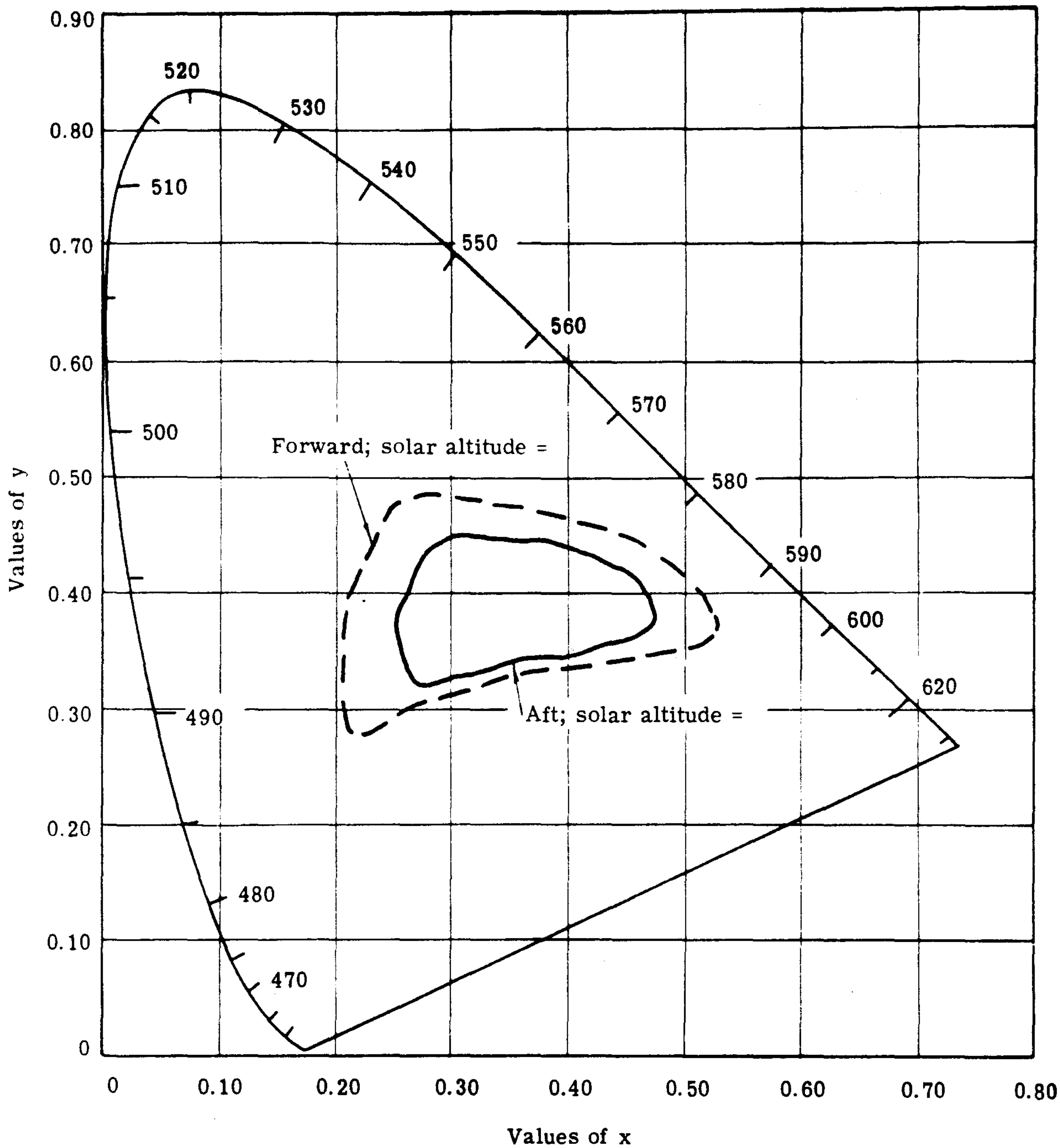

Fig. 3-11 — System gamut of colors for best exposed frames

4. SUBJECTIVE EVALUATION

The SO-121 collected in this test was evaluated by an experienced photointerpreter.* The purpose of this analysis was to provide relative statements as to the general kind of information obtainable from the SO-121 at the several solar altitudes. It is realized that this analysis is not quantitative in nature, but it does allow some generalized statements about the usefulness of color at low solar altitudes and the effect of underexposure, overexposure, and the atmosphere on photointerpreter usability.

4.1 EVALUATION PROCEDURE

The photointerpreter examined the imagery on a Richards light table at magnifications from 7× to 30×. Each exposure run was evaluated with its companion run alongside. Aspects investigated affecting image interpretation included color, contrast, resolution, illumination, shadow length, and skylighting.

4.2 EXPOSURE COMMENTS

The photointerpreter's general comments on the exposure of each pass are listed in Table 4-1.

From this analysis it can be seen that the photointerpreter considered the well exposed photography (considering both cameras) to run from 8.6 degrees solar altitude (Pass 2, aft-looking camera) to 28.7 degrees solar altitude (Pass 6, forward-looking camera).

4.3 RESOLVING POWER EVALUATION

CORN T-bar targets were recorded on the photography and read by experienced readers. The results listed below represent the best resolved target element and not the average of the best resolved in both directions. This is considered fair since this was meant to be a test of resolution versus solar altitude and exposure, and not a test of system capability. The results obtained are recorded in Table 4-2.

The ground resolved distances are equal to a bar and a space. Comparing the resolution figures with the exposure evaluation, it appears that best resolution occurs at, or very near, the optimum exposure level for good interpretation.

4.4 PHOTOINTERPRETER EVALUATIONS

Since there are so many factors affecting the usability of the test photography, a subjective

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* The particular photointerpreter employed is trained in the use of color photography so that unfamiliarity with the medium was not a problem.

Table 4-1 — Photointerpreter's General Comments on Exposure

Pass Number	Solar Altitude, degrees	Forward-Looking Camera	Aft-Looking Camera
1	5.2 to 5.9	Threshold exposure	Well underexposed
2	8.6 to 11.6	Well underexposed	Good exposure
3*	13.9 to 14.7	Underexposed but usable	Good exposure
4	17.9 to 20.5	Slightly underexposed	Overexposed
5†	22.9 to 23.7	Very good exposure	Overexposed
6	26.2 to 28.7	Very good exposure	Well overexposed
7	31.2 to 32.1	Good exposure with qualifications	Well overexposed
8	34.7 to 37.3	Good exposure with qualifications	Very much overexposed
9			Very much overexposed
10			Very much overexposed

*Nominal correct exposure for slit used with aft camera.
†Nominal correct exposure for slit used with forward camera.

Table 4-2 — Resolution Versus Solar Altitude

Solar Altitude, degrees	Forward-Looking Camera Resolution, feet	Aft-Looking Camera Resolution, feet
6	8	5
10	4	2.8
14	3.5	2.5
19	5	2.5
23	2.5	2.8
27	3.3	2.8
31	3.3	3.3
36	3.5	3.3

evaluation of each run will present facets that cannot be described quantitatively. Note that all times have been converted from Greenwich time to local standard time for Bakersfield, California. (119 degrees W longitude requires a subtraction of 7 hours 55 minutes from Z time.)

4.4.1 Forward-Looking Camera (with 0.35 ND filter)

Run 1 (Sun angle: 5.2 to 5.9 degrees; time: 5:33 to 5:40 a.m.; exposures 0027 through 0083)

The sun is just above the horizon and only the high ridges of hills show any direct illumination. Exposure range is very low, restricting the useful range of the film. Buildings, tanks, and other landmark structures having highly reflective surfaces are quite prominent due to skylighting.

First class road networks can be delineated and oil extraction areas can be located, but not detailed.

Airfield runways and taxiways can be delineated and aircraft can be located, but not identified.

Run 2 (Sun angle: 8.6 to 11.6 degrees; time: 5:54 to 6:06 a.m.; exposures 0103 through 0160)

The sun is above the horizon and the exposure level is still too low, with few colors decernible and low contrast. The general appearance of the photography is muddy. High reflectance objects stand out against the dark background. Most structures are ill defined and shadows do little to aid interpretation.

Run 3 (Sun angle: 13.9 to 14.7 degrees; time: 6:18 to 6:26 a.m.; exposures 0174 through 0226)

Photography is still underexposed, but there is good color saturation in aircraft and their service vehicles. Structural details as depicted by shadows are about the threshold of usability.

High reflectance and landmark items are well defined.

The physiography of the hill areas is fairly well shown and the drainage pattern is easily traced.

Run 4 (Sun angle: 17.9 to 20.5 degrees; time: 6:42 to 6:50 a.m.; exposures 0234 through 0282)

Photography is slightly underexposed with nicely saturated colors. Color and density are very good in the hills and open places away from the urban areas.

The physiography is a little dark, but well modeled except in heavily wooded sections where the cover makes light penetration difficult. Shadows of structural details are increasing in sharpness, and oil well derricks are well defined.

Run 5 (Sun angle: 22.9 to 23.7 degrees; time: 7:03 to 7:10 a.m.; exposures 0291 through 0343)

The photography has very good color saturation and contrast with pastels showing well. Good to excellent edge contrasts are present and the length and sharpness of structural shadows are good for identification purposes. Industrial areas are well defined as are the hills without vegetation.

Color quality, exposure level, and sun angle combine to make this the best run of the series.

Run 6 (Sun angle: 26.2 to 28.7 degrees; time: 7:23 to 7:32 a.m.; exposures 0344 through 0404)

This run has very good exposure in the urban area with good contrast and detail in closely built areas.

Airfield facilities, runways, taxiways, and aircraft are well depicted.

Shadows are becoming too short for use in structural interpretation of bridge understructures.

The hills show good relief shadowing, but areas of dense cover are still dark.

Run 7 (Sun angle: 31.2 to 32.1 degrees; time: 7:44 to 7:52 a.m.; exposures 0413 to 0466)

The visual appearance of this area, without magnification, is quite good. However, under close inspection, the colors are becoming desaturated and contrasts are declining.

Closely built-up urban areas are well defined since they are darker than the general subject matter and overexposure tends to help them.

Structural shadow details are good in free standing items such as oil derricks, but are almost useless in bridges and the like where the open structure is underneath.

Physiographic modeling is fair and heavily wooded areas show very good detail.

Run 8 (Sun angle: 34.7 to 37.3 degrees; time: 8:05 to 8:13.5 a.m.; exposures 0471 through 0528)

This run is similar in color and appearance to Run 7. The details in dark wooded areas are at their best, but no shadows are ever penetrated.

Shadows are more normal now with not too much exaggeration, especially with aircraft. Bridge shadows are lost, but those of the derricks are still good.

4.4.2 Aft-Looking Camera (without ND filter)

Run 1 of 10 (Sun angle: 5.2 to 5.9 degrees; time: 5:33 to 5:40 a.m.)

The sun is too low to cast shadows in the urban area, but hill tops are illuminated. There is more exposure to this roll than to its companion roll in the aft-looking slave unit. Color is evident and buildings with high reflectivity or gross size are easily detected, but aircraft and small items escape positive identification.

Roads show well enough for delineation as do runways and taxistrips. Oil extraction areas can be located and individual sites shown but no detail is evident.

Run 2 of 10 (Sun angle: 8.6 to 11.6 degrees; time: 5:54.5 to 6:06 a.m.)

This run, overall, is fairly well exposed. Airfield facilities are well defined and have good detail separation by color and brightness. Service facilities and aircraft stand out well. Good shadow length and sharpness aid in identification of many objects, particularly oil well derricks and bridge understructures.

There is good modeling in the topography and shadows appear somewhat luminous.

Run 3 of 10 (Sun angle: 13.9 to 14.7 degrees; time: 6:18 to 6:26 a.m.)

The general overall appearance of this run is one of good exposure, but magnification reveals a loss of color saturation in most items.

Urban areas with closely packed details are blocked in shadow areas while large shadow areas show good illumination.

Run 4 of 10 (Sun angle: 17.9 to 20.5 degrees; time: 6:42 to 6:50 a.m.)

The overall exposure for this run is too great; however, the cluttered urban areas show somewhat open shadow detail. Colors are desaturated in most places, but the heavily forested hills are nicely exposed.

Run 5 of 10 (Sun angle: 22.19 to 23.7 degrees; time: 7:03 to 7:10 a.m.)

Shadow areas are quite open and wooded hills show the best so far. General overexposure has resulted in loss of color saturation and tends to lower separation of closely related density areas, i.e., adjacent buildings, soil differences, etc.

Run 6 of 10 (Sun angle: 26.2 to 28.7 degrees; time: 7:23 to 7:32 a.m.)

Overexposure has caused a decrease in color saturation. The higher solar altitude is providing better illuminated shadows of decreased length, but items such as biplanes are well identified.

Individual trees now show in groves due to longer exposure, but contrast in foiling and the overall image value is degrading.

The length of shadows is still good for identification purposes, but they are lacking in contrast.

Run 7 of 10 (Sun angle: 31.2 to 32.1 degrees; time: 7:44 to 7:52 a.m.)

Far too much exposure is evident with washed out color and low contrast.

The heavy hill vegetation is excellent with about optimum exposure for this feature.

Generally, this is poor material for interpretation.

Run 8 of 10 (Sun angle: 34.7 to 37.3 degrees; time: 8:05 to 8:13.5 a.m.)

Essentially, the photography is the same as that of Run 6 of 10.

Run 9 of 10

This run covers desert areas and Edwards Air Force Base. It is well overexposed with the attendent loss of color and contrast.

Run 10 of 10

This is a desert run also, overexposed and about the same as Run 9 of 10.

4.4.3 Examples

Figs. 4-1, 4-2, and 4-3 are selected examples of photography from this test. The three prints illustrating Runs 1 of 10, 5, and 8 were made through a color negative intermediate stage. They are the results of extensive color correction tests and represent the best compromise print in the opinions of three observers.

In print no. 1 (Run 1 of 10, Fig. 4-1), the green overcast color present throughout the test has been generally eliminated. Details have been enhanced by integration in the printing process, and the print is more pleasing to the eye and more easily read than the original transparency.

In print no. 2 (Run 5, Fig. 4-2), some of the green cast is still present but translated more to the cyan. Although the concrete aircraft parking aprons, representing an intermediate neutral,

Fig. 4-1 — Selected photographic example of aft-looking camera tests at a solar altitude of 5.9 degrees (Run 1 of 10)

Fig. 4-2 — Selected photographic example of forward-looking camera tests at a solar altitude of 23.7 degrees (Run 5)

Fig. 4-3 — Selected photographic example of forward-looking camera tests at a solar altitude of 37.3 degrees (Run 8) show with a cyan cast, the white signs show more neutral. Lawns and trees are more naturally green and differences in vegetation throughout the print are more pronounced.

Print no. 3 (Run 8, Fig. 4-3) is another example of image enhancement by using the intermediate color negative method. The original transparency is somewhat thin with lower saturation and contrast. The green overcast seems to have been minimized in overexposure but natural and cultivated vegetation suffers as a result. Neutrals are rendered more naturally and this may be a fringe benefit of overexposure with this emulsion.

5. KH-4b SYSTEM CONSIDERATIONS

The photography and data obtained with EKIT flight test no. 1 was evaluated to allow specification of the impact on the KH-4b system. In particular, we were interested in determining: (1) the expected resolution performance of SO-121 film in the KH-4b system at low solar altitudes, (2) the proper exposure of SO-121 as a function of solar altitude, and (3) the proper color filtration at low solar altitudes.

5.1 RESOLUTION

The ground resolution was evaluated for each pass over the CORN target area and for each camera. These ground resolution numbers (see Section 4.3) were then converted to film resolution (in lines per millimeter) by knowing the altitude of the flight and the focal length of the lens that was used.

The number of the last frame for each pass and the Greenwich time at the end of each pass were recorded. We assumed that the last frame for each pass was photographed at the absolute local time corresponding to the Greenwich time at the end of the pass. The cycle period of the cameras was set at Mode II (8 seconds) so that successive frames are separated by 8 seconds. For each pass, the number of the frame in which the resolution targets appear is also known. Thus, the time lapse between the frame that contains the resolution targets and the last frame for each pass was readily computed. In this manner we were able, for each pass, to determine the absolute local time when the targets were photographed. Then, using the absolute local times and the formula

$$\sin h = \cos \phi \cos \delta \cos 15t + \sin \phi \sin \delta \quad (5.1)$$

where h = solar altitude
ϕ = north latitude
δ = solar declination
t = time difference from noon, hours

we calculated the solar altitudes at which the targets were photographed. Table 5-1 shows the calculated solar altitudes for each pass and the resolutions that were achieved in the test.

Therefore, by knowing the solar altitude and the resolution for each pass, we were able to plot resolution versus solar altitude for both cameras. These two curves are shown in Fig. 5-1.

The slit widths of both cameras were equal but the forward-looking camera carried an additional 0.35 ND filter. From the photography obtained it appears that pass no. 3 was the best exposed for the aft-looking camera while pass no. 5 was the best exposed for the forward-looking camera. This difference between the two cameras is primarily explained by the presence of the neutral density filter in the forward-looking camera.

Table 5-1 — Recorded Resolving Powers

Pass No.	Solar Altitude, degrees	Forward Camera Resolution, lines per millimeter	Aft Camera Resolution, lines per millimeter
1	5.7	13	21
2	11.1	26	38
3	15.7	31	43
4	19.9	21	43
5	24.5	43	38
6	28.2	32	38
7	33.0	32	32
8	36.7	31	32

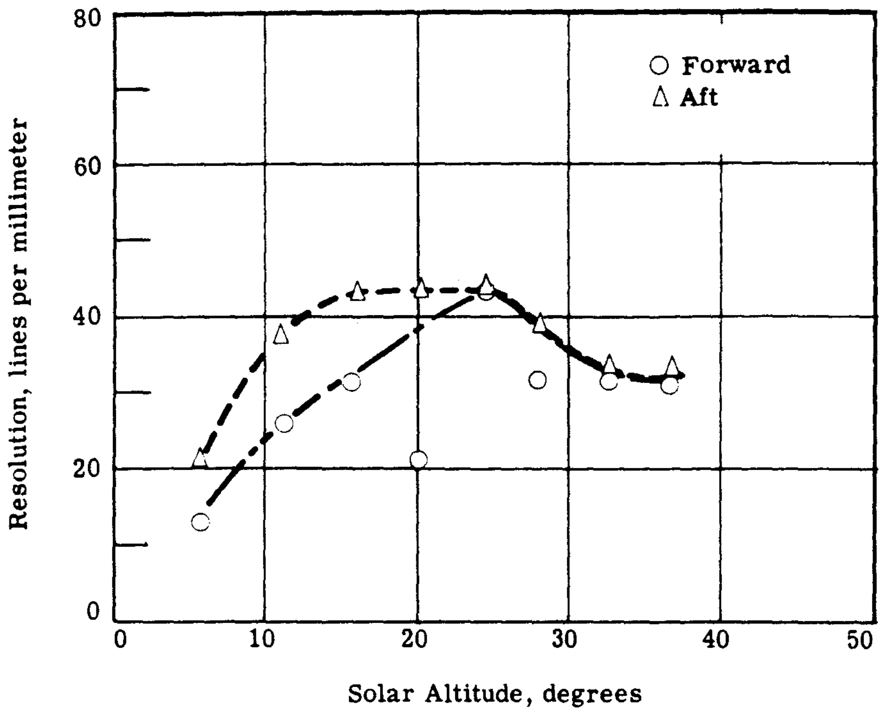


Fig. 5-1 — Observed film resolution of CORN targets

The resoltuion achieved with either camera (Fig. 5-1) depends on the following factors: resolution of the lens and filter, target contrast, atmospheric luminance, horizontal illumination falling on the target, film resolution and exposure of the film. In most of the passes over the targets, the film in both cameras was either underexposed or overexposed. Improper exposure of the film reduces the resolution that would have otherwise been achieved. Thus, in Fig. 5-1 the variation of resolution with solar altitude results from both improper exposure and the apparent change of target contrast due to the atmosphere. It is desirable to determine what the resolution would have been at various solar altitudes if the film had been properly exposed, and what is the ultimate resolving capability of SO-121 at low sun angles. To obtain these relationships we utilized the gray scale targets. The densities of the images of these targets can be measured with a microdensitometer. Exposure values corresponding to the measured densities can then be obtained using a D-log E curve. Unfortunately, a single D-log E curve could not describe the sensitometric behavior of SO-121 over all solar altitudes. The luminous density curve of SO-121 is the most useful curve but varies with solar altitude and target reflectance because it depends on the spectral distribution of the light source for which it is determined.

[redacted] provided a sensitometric strip of processed SO-121. This film strip had been exposed to a light source simulating daylight. The luminous density of each step in the sensitometric strip as well as its density for a very narrow band green light source were measured. Two curves were then plotted:

1. Luminous density versus log exposure
2. Green density versus log exposure

We found that the two curves are fairly close together over their linear portions and deviated slightly only for high and low densities. Thus, it appears possible to substitute the green densities for luminous densities at least over the linear part of the D-log E curves. Since the luminous densities of the CORN targets were not measured, we have used the green densities which were available and the green D-log E curve.

Another difficulty with the D-log E curve is the fact that the sensitometric strip was exposed to a source which simulates daylight (about 5900 °K) while the light which produced the target images on the film is of higher color temperature because of the atmospheric luminance. This is especially true at very low solar altitudes.

The resolution targets consist of black (4-percent reflectance) and gray (37-percent reflectance) patches. The gray scale targets are extended areas with reflectances of 4, 8, 16, 32, and 64 percent. The green densities of the images of the gray scale targets were plotted against their respective reflectances for each camera and each pass. From these curves we were able to obtain the green densities of extended ground areas with reflectances of 4 and 37 percent. Then, using the green D-log E curve, we found the difference in log-E between a 4- and a 37-percent reflectance target. The antilog of this value is the apparent contrast of the resoultion targets. The ground contrast of the resolution targets is 37/4 or 9.25. However, the atmospheric luminance reduces this contrast, and the apparent target contrast that the lens sees is lower and varies with solar altitude. Thus, from the green density data we can determine the apparent target contrast versus solar altitude for both cameras. These two curves are plotted in Fig. 5-2. A theoretically determined apparent target contrast curve is plotted in the same figure. It is observed that the experimental curves agree very well with the theoretical curve over the solar altitudes for which the resolution targets (20.5-percent average reflectance) are not seriously underexposed or overexposed.

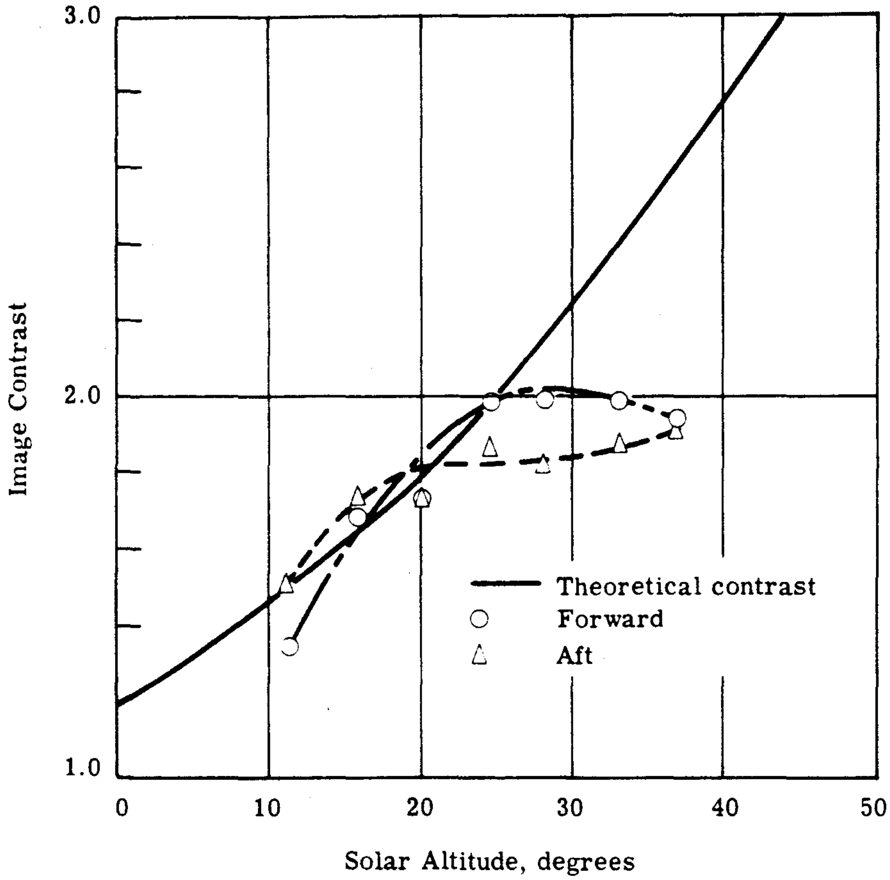


Fig. 5-2 — Image contrast derived from both cameras compared to theoretical image contrast

Fig. 5-3 shows the expected maximum log resolution of SO-121 versus the target log modulation. This curve assumes that the lens has very high resolution compared to the film and that the film is properly exposed.

Combining Figs. 5-2 and 5-3 produces Fig. 5-4 which contains three curves corresponding to the three curves of Fig. 5-2. Each curve shows what the maximum resolution versus solar altitude would be for the targets used in this test if the film was properly exposed and the lens was perfect. The difference in the resolutions between Figs. 5-1 and 5-4 should be due to the lens (focusing) and the improper exposure of the film. From the measured density data it appears that in the aft-looking camera the resolution targets are fairly well exposed for solar altitudes between 10 and 20 degrees while in the forward-looking camera the resolution targets are well exposed for solar altitudes between 16 and 25 degrees. Therefore, in this solar altitude range, the degradation of the resolution can be attributed to the lenses. Taking advantage of this situation the lens resolutions from Figs. 5-1 and 5-4 can be calculated using the formula

$$\frac{1}{R_m^2} = \frac{1}{R_l^2} + \frac{1}{R_f^2} \qquad (5.2)$$

where R_m = measured resolution (see Fig. 5-1)
R_l = lens resolution
R_f = film resolution (see Fig. 5-4)

The result is shown in Table 5-2.

The resolutions of the lenses decrease at low solar altitudes mainly because the apparent target contrast decreases at these altitudes.

In the past, two typical 24-inch Petzval lenses were tested with SO-121. The results of these tests are included here for comparison with the results shown in Table 5-2. Lens I-23 with SO-121 film and a Wratten no. 2E filter has a low contrast (2:1) resolution of 50 lines per millimeter. Lens J-37 with SO-121 and a no. 2E filter has a low contrast resolution of 66 lines per millimeter. Now the forward-looking camera lens with SO-121 and a Wratten no. 2E filter has a resolution of 43 lines per millimeter for a 2:1 target contrast (see Figs. 5-1 and 5-2). Lens I-23 was tested under static conditions while lens J-37 was tested under dynamic conditions. The resolution of J-37 under static conditions should theoretically be larger than 66 lines per millimeter. However, this resolution is already quite low and it is not affected appreciably by the blur introduced by the camera operation. Thus, we may assume that the resolution of J-37 under static conditions is also 66 lines per millimeter. Therefore, the difference in resolution between I-23 and J-37 should be attributed to manufacturing tolerances. Also, in Table 5-2, we see the same difference in resolution between the aft-looking camera lens and the forward-looking camera lens. Therefore, a basic conclusion is that the performance of Petzval lenses with the SO-121 and a Wratten no. 2E filter is expected to vary significantly since the lenses are built to meet only certain resolution requirements when used with 3404 film and a Wratten no. 21 filter.

The position of the focal plane in a Petzval lens for monochromatic light entering the lens as a parallel beam depends on wavelength. It was found that the focal plane moves away from the lens as the wavelength increases from the blue region of the spectrum towards the red. In other words, the focal length of the Petzval is longer for red light than for blue light. Hence, the position of best focus of the lens with a Wratten no. 21 filter is different than its position of best focus with

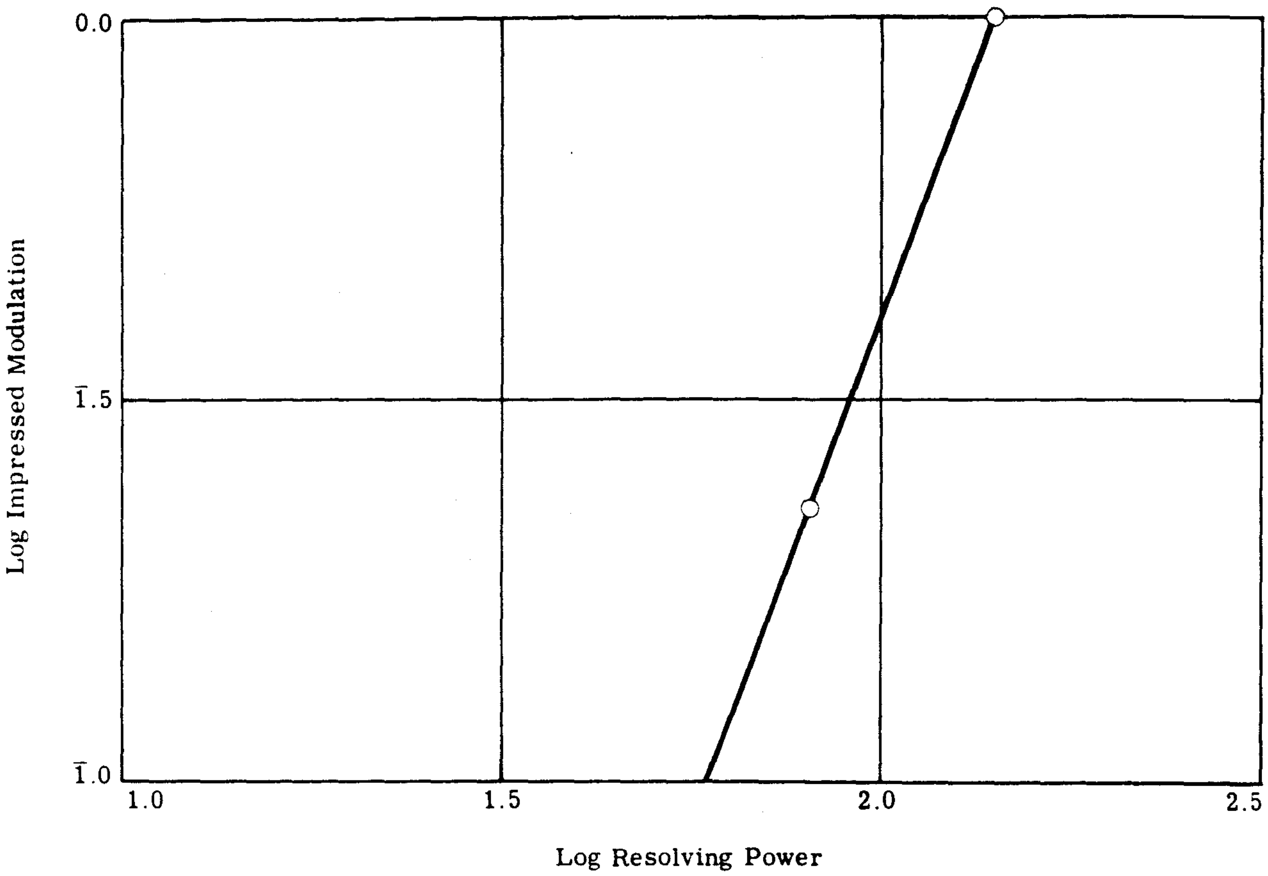


Fig. 5-3 — Log modulation of target versus log resolution (lines per millimeter) for SO-121 film

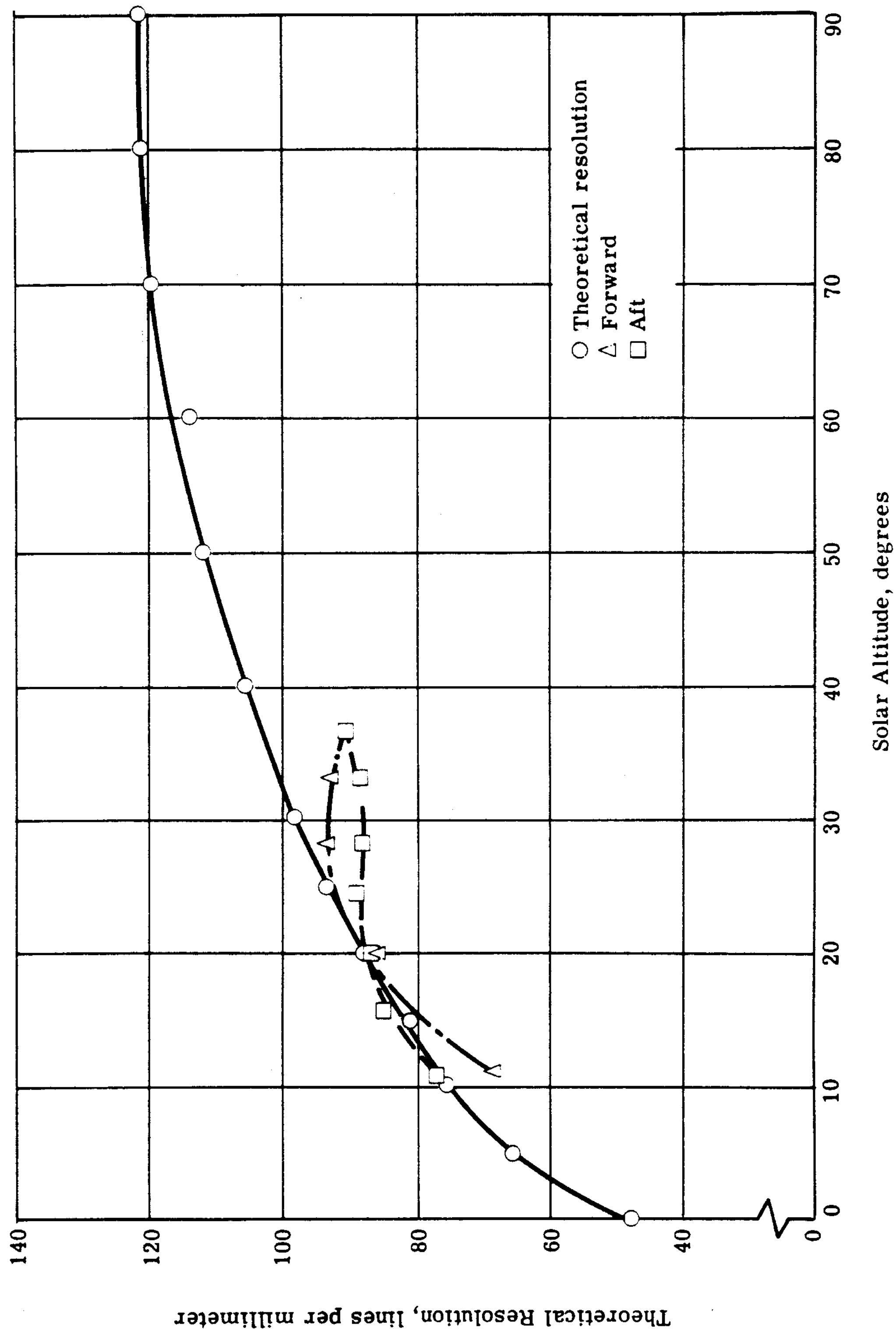


Fig. 5-4 — Theoretical resolution assuming perfect optical system

Table 5-2 — Lens Resolution (including defocused condition)

Solar Altitude, degrees	Aft-Looking Camera, lines per millimeter	Forward-Looking Camera, lines per millimeter
11.1	44	–
15.7	50	34
19.9	49	42
24.5	–	48

a Wratten no. 2E filter. Lenses I-23 and J-37 were focused with a no. 2E filter while the forward-looking camera lens was initially focused with a Wratten no. 21 filter. Thus, the forward-looking camera lens must have been slightly out of focus during the test, which perhaps accounts for the lower resolution that was achieved (43 lines per millimeter versus 50 lines per millimeter for I-23 and 66 lines per millimeter for J-37).

Furthermore, lens I-23 was tested and its MTF at various regions of the spectrum was measured. In each case the focal plane was adjusted for best focus. The measurements show that the MTF of this lens in the blue region of the spectrum is significantly lower than its MTF at either the green or the red regions. Therefore, the resolution of this lens with a no. 2E filter, SO-121, and a 2:1 target contrast varies slowly with the color temperature of the light source illuminating the target. High color temperature sources (bluish in color) would result in lower resolutions than if the illuminating source was daylight. The resolutions of I-23 and J-37 were obtained with a source simulating daylight while the comparable resolution of the forward-looking camera was obtained at a solar altitude of 24.5 degrees where the apparent target illumination has a color temperature higher than the color temperature of daylight. Thus, we should expect the resolution of the forward-looking camera lens to be degraded by this effect. However, we anticipate that this degradation is very small, if not negligible.

The conclusion reached from the above analysis and data is that in the KH-4b system, a gross estimate of the expected resolution with SO-121 film and a Wratten no. 2E filter (at an apparent target contrast of 2:1) is:

1. 40 to 50 lines per millimeter for a dual mission (3404 and SO-121, lens focused for a Wratten no. 21 filter)
2. 50 to 60 lines per millimeter for a full color mission (lens focused for a Wratten no. 2E filter)

5.2 EXPOSURE

As mentioned earlier, the exposure time for both cameras remained unchanged over all the passes and, consequently, nominally only one pass in each camera was properly exposed, while the rest were either underexposed or overexposed. For the passes in which the general picture quality was best, the 10 percent reflectance targets achieved densities in the middle of the linear range of the green D-log E curve. Thus, it can be concluded that the average ground reflectance in the test is approximately 10 percent.

We have assumed that the targets of interest in the KH-4b system have an average reflectance of 15 percent. For this reflectance value, pass no. 4 (19.9 degrees solar altitude) was the best exposed in the forward-looking camera. From the green densities of the gray scale targets, the green density had a 15-percent reflectance area for every pass. Using the green D-log E curve allowed conversion of these density values into log exposure values. Subtracting the log E of each pass from the log E for pass no. 4 provided a Δ-log E number. The antilog of this number is the ratio of the exposure time required for correct exposure of a pass to the exposure time of pass no. 4. The exposure time for pass no. 4 is 1/600 second or 1.67 milliseconds. If the 0.35 ND filter was not used, then the correct exposure time for pass no. 4 would have been 0.75 millisecond. Since the correct exposure time for pass no. 4, and the ratios of the required exposure times for the other passes to the exposure time for pass no. 4 are known, the required exposure time for each pass can be determined by multiplying the ratio of the exposure times by

0.75 millisecond. The result is the curve shown in Fig. 5-5 which shows what the exposure time should be versus solar altitudes in order to properly expose a 15-percent ground reflectance target.

It should be pointed out that the curve in Fig. 5-5 represents the effects of the atmospheric conditions existing during the test which may not be typical of other areas of the world at different times of the year. For example, the target area flown in the test has a fairly dry climate, drier than other areas of interest to the KH-4b system but not as dry, for example, as the North African coast. If the atmosphere was hazier, the curve in Fig. 5-5 could be expected to rise more slowly at low sun angles.

A similar curve for the aft-looking camera data could also have been plotted on Fig. 5-5. This was not done since the film in the aft-looking camera was overexposed for passes no. 4 through 8. Nevertheless, the accuracy of the curve in Fig. 5-5 can be checked as follows. Compare the green densities of the 15-percent reflectance target in the aft-looking and forward-looking cameras. Select a density as close to the center of the linear range of the green D-log E curve as possible. In the aft-looking camera, the 15-percent reflectance target achieved a density at a solar altitude of 11.1 degrees equal to the density achieved by the same target at about 27 degrees solar altitude in the forward-looking camera. The ratio of the required exposure times at 11.1 and 27 degrees can be determined from Fig. 5-5. This ratio is 2.35 and corresponds to a neutral density of 0.37. This corresponds well to the 0.35 neutral density filter that was used in the forward-looking camera. Therefore, two widely separated points in the curve of Fig. 5-5 have approximately the correct exposure ratio.

Fig. 5-5 also shows a stepped exposure function with four steps corresponding to the four possible exposure slits available for a full color mission in the KH-4b system. The ratio of the maximum step to the minimum step is limited by the maximum (0.340 inch) and the minimum (0.134 inch) slits available in the KH-4b instruments. Actually, depending on the required scanning rate, a neutral density filter would have to be used in the KH-4b instruments. This filter will change the exposure time scale in Fig. 5-5 but will not affect the shape of the curves. As shown in Fig. 5-5 it will be possible, in a full color mission with the four exposure steps, to obtain photography from 8 to 90 degrees solar altitude without having the film underexposed or overexposed by more than 1/5 of a stop at the most.

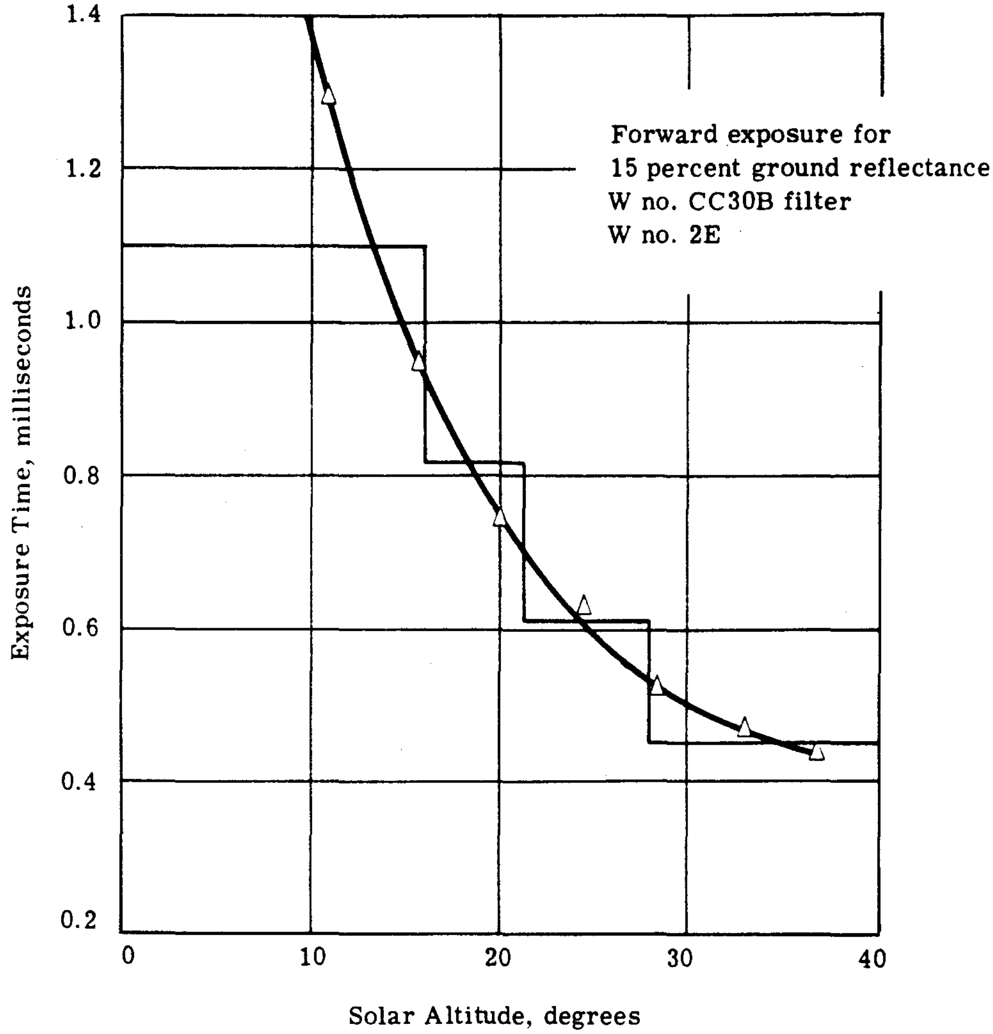


Fig. 5-5 — Required exposure time for film SO-121 versus solar altitude

6. CONCLUSIONS

This test generated a great deal of useful data that could be used to draw many conclusions about a wide range of subjects. However, the main purpose of the test was to evaluate the performance of SO-121 at low solar altitudes and to relate this performance to the KH-4b camera system. Our conclusions in the main, therefore, will be restricted to those relevant to the KH-4b system. The main conclusions of the test are as follows.

1. SO-121 can be generally employed at solar altitudes as low as 10 degrees. For certain conditions SO-121 can be usefully employed at lower solar altitudes. Certain types of information are recorded at solar altitudes as low as 5 degrees. The one case of a picture taken with no direct illumination and a slow scan velocity illustrated what could be done if the system could operate under these conditions.

2. In the KH-4b system, a full load of SO-121 could be properly exposed (by slit control) to solar altitudes as low as approximately 13 degrees. Exposures at 10 degrees solar altitude would be quite acceptable, being only about 1/5 of a stop underexposed.

3. The maximum resolution that could be expected with SO-121 in the KH-4b camera (assuming correct exposure and correct lens) is approximately 60 lines per millimeter. The system will achieve a higher resolution with a Wratten no. 4 filter than with the Wratten no. 2E currently being used. This higher resolution is due to the fact that the MTF of the lens is higher with a Wratten no. 4; the apparent ground contrast will be somewhat higher, and the focus shift of the lens is smaller with the no. 4 than with the no. 2E. For a full color mission, the Petzval lens should be refocused for the combined color correction and haze attenuating filters.

4. Color reproduction is poor (restricted) at very low solar altitudes when using the nominal color compensating pack. A separate color correction pack should be used for these cases. This pack is practical for a full color mission, but impractical with a split load of black and white and color films.

5. Improper exposure affects both resolution and color balance. This, of course, is not startling but it is interesting to note that perfect color balance is not a prerequisite to obtaining useful photography for photointerpretation uses. Further, it should be noted that, by selective printing, many of the poor color balance originals could be corrected quite well to produce a properly balanced print.

6. The limitations on the quality of the resultant SO-121 photography due to the lens are apparent. The Petzval was not designed to be well corrected for the blue region. It would be worthwhile to consider what improvements might be effected by using a specially designed color corrected lens with the SO-121.

7. The contribution of the blue image is relatively small. The contrast attenuation of the atmosphere in this region is significant, and causes this effect. Information content would seem to be affected little, and color balance enhanced, by the use of a Wratten no. 4 filter instead of a Wratten no. 2E. However, for a partial color mission (when only one filter pack could be used), the use of a Wratten no. 2E would be acceptable at low solar altitudes.

Again, it should be emphasized that these conclusions can only be accepted in a general way. This test was run with one particular emulsion batch of SO-121. There is no guarantee that successive batches of SO-121 will be exactly like this one. However, barring a major change in the product, the conclusions should be generally valid.

Appendix A

A BRIEF SUMMARY OF COLOR DENSITOMETRY

In comparison to the standard black and white densitometry which we are all familiar with, color densitometry is a relatively complicated field of endeavor. The prime reasons for the complications are: (1) the fact that color as well as brightness differences are now involved, and (2) the fact that the components of the image are three colored dyes arrayed in individual layers. Because of the inherent complexity of the evaluation of such imagery, many different densitometric techniques for the evaluation of color images have been generated, each with a specific purpose. These notes have the prime purpose of discussing some of these densitometric techniques as applied to the evaluation of images on color film.

1. INTEGRAL DENSITIES

There are basically two types of color densitometry—integral and analytical. Integral densities describe some action of the color image as a whole, and they do not directly yield information about the amounts of the individual colorants of which the image is composed. There are five different types of integral densities.

1.1 Integral Printing Densities

Density measurements are made in a densitometer whose response matches a given printing material.

1.2 Colorimetric Densities

These densities are measured with a filtered photocell to match the standard ICI colorimetric responses of a standard observer.

1.3 Luminous Densities

Luminous density is the apparent density of a colored object in respect to the standard ICI observer. This density does not take into account the color of the material. It may be measured electrically or visually.

1.4 Arbitrary Three Filter Densities

These densities are measured in a densitometer with three arbitrary red, green, and blue wide bandpass filters. They do not correspond to any specific film usage. These densities are primarily useful in quality control where the only information of interest is to determine if today's run is the same as yesterday's.

1.5 Integral Spectral Densities

These densities are a fundamental measurement of the film. They are measured in a densitometer to very narrow bandpass filters, preferably monochromatic light.

2. ANALYTICAL DENSITIES

Integral densities always describe some action of the color image as a whole. They do not directly yield information about the image composition in terms of the individual amounts of dye. A subtractive color process image is thought of as composed of cyan, magenta, and yellow dye, and with certain reservations, this is correct. The cyan dye primarily absorbs red light, the magenta dye primarily absorbs green light, and the yellow dye primarily absorbs blue light. To a smaller extent, however, the cyan dye absorbs also green and blue light, the magenta dye absorbs red and blue light, and the yellow dye absorbs green and red light. These absorptions are known as the "unwanted" absorptions of the various dye layers. Integral density measurements show the total effect of all these absorptions. Analytical density measurements determine the individual amounts of each of the three dye deposits. The amounts of dye deposits determined then can be expressed in any of several useful density units.

2.1 Spectral Analytical Density

The amount of each dye is expressed as a function of wavelength.

2.2 Equivalent Neutral Density

The amount of the dye is expressed as the luminous density of the gray image that would be formed by adding to the single dye deposit sufficient quantities of the other dyes of the color process to form a neutral.

2.3 Equivalent Neutral Printing Densities

Same as the above except adding sufficient amounts of the various dyes to obtain an image with the R, G, and B printing densities equal.

3. SPECTRAL ANALYTICAL DENSITIES

Various analytical densities differ from each other in the type of measure in which the amounts of each of the dyes are expressed. One of the simplest types of measure is the spectral analytical density, or the density of the dye at some particular wavelength. The amount of cyan dye, for example, in a given piece of film may be expressed in terms of the density which this dye has at, say 650 millimicrons. Usually the wavelengths chosen for routine analysis of the spectral analytical densities of emulsions correspond to the peak wavelength of dye absorption. The basic calibration of the dye layers in a color film is a plot of the spectral analytical density versus wavelength.

4. EQUIVALENT NEUTRAL DENSITIES

Probably the most useful of the analytical densities is the equivalent neutral density. This density is defined as the visual density the photographic image should have if it were converted to a neutral gray by superimposing the just required amounts of the fundamental colors of the process.

The relationship between equivalent neutral densities and the spectral density of a selected set of dyes is illustrated in Fig. A-1. The curves c, m, and y show the spectral analytical densities of the cyan, magenta, and yellow dyes which together form the neutral shown by curve n. For the example, the luminous density of the curve n is 1.0. In accordance with the definition of END, each of the component dye layers also has an END of 1.0 regardless of the absolute value of spectral analytical density for that dye layer.

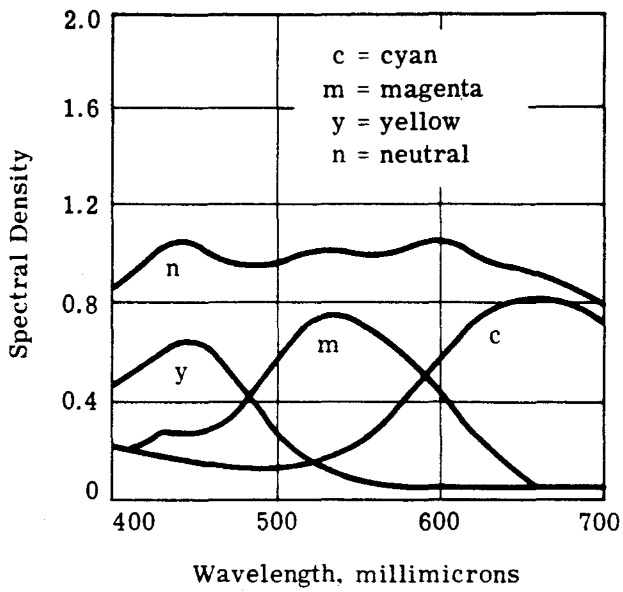
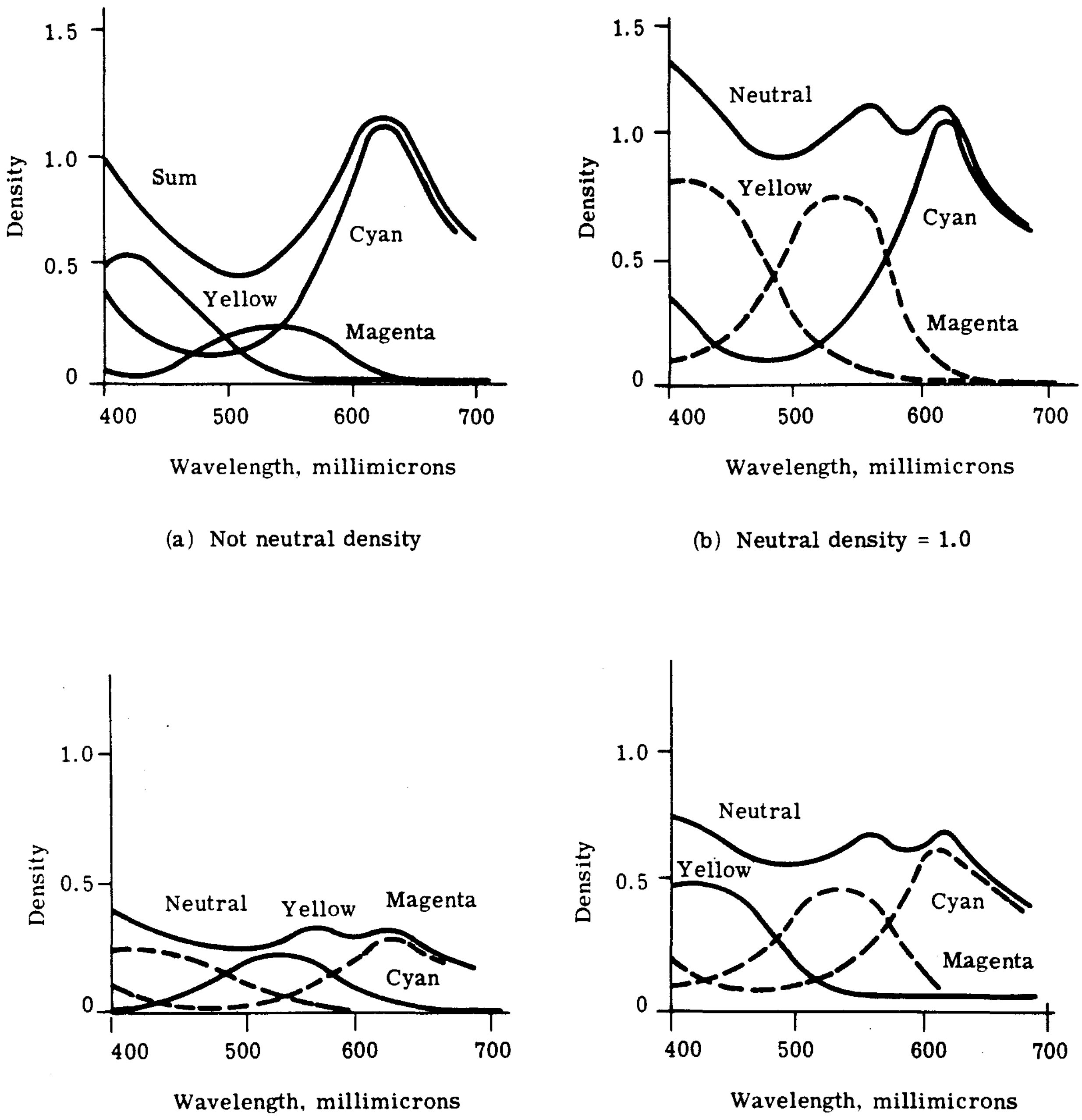


Fig. A-1 — Spectral density of a selected set of dyes

A combination of different amounts of these dyes is shown in Fig. A-2 (a, b, c, d). As is evident from the new concentrations (Fig. A-2a) this sample is not neutral. In Fig. A-2b, the cyan dye is shown by the solid curve and sufficient amounts of magenta and yellow dyes to make a neutral are shown by the dashed curves. The density of this neutral is 1.0. The END of the cyan component of the Fig. A-2a example is therefore 1.0.

Fig. A-2c shows the magenta dye for Fig. A-2a and the corresponding amounts of cyan and yellow dyes necessary to give a neutral. The luminous density of this neutral is 0.3. The END of the magenta layer shown in Fig. A-2a is therefore 0.3.

Similar combinations to give a neutral for the yellow dye are shown in Fig. A-2d. The luminous density of this neutral, and consequently the END of the yellow dye in Fig. A-2d is 0.6



(a) Not neutral density

(b) Neutral density = 1.0

(c) Neutral density = 0.3

(d) Neutral density = 0.6

Fig. A-2 — Combinations of different amounts of dyes

5. INTEGRAL DENSITIES AS A FUNCTION OF DYE SPECTRAL ANALYTICAL DENSITY

Assuming that for many applications the END's of a particular image are of most benefit, the question becomes how to determine such densities. It has already been shown that END's can be determined knowing the spectral analytical densities of the dye layers composing a particular image on the film. The problem is that spectral analytical densities are impossible to measure directly on a piece of color film after an image has been exposed and developed for the intended use. The type of measurements that can be made, however, are integral spectral densities. A later section will illustrate how one can determine the spectral analytical densities from the integral analytical densities, and then how the equivalent neutral density (END) can be determined from the integral spectral density. It is sufficient to point out at this time that these conversions are possible solely because photographic dyes used in color films obey within reason the log-D law, that is, as the concentration of a dye changes, its density changes linearly. For example, if the concentration of a dye in the color film is doubled, its density is also doubled.

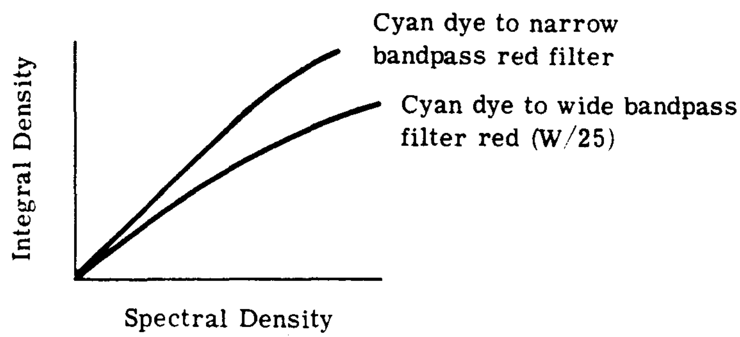


Fig. A-3 — Relationships between the spectral analytical density of a cyan patch and the integral spectral density

It is extremely important to understand first, however, that integral densities (spectral or otherwise) are not strictly valid when measured with wide bandpass filters, due to the nonlinear density response when compared with pure spectral (monochromatic) light densities. For example, Fig. A-3 illustrates the relationships between the spectral analytical density of a cyan patch and the integral spectral density when the integral density is measured with filters of differing bandwidth. As indicated in Fig. A-1, the integral spectral density of a color film at a given wavelength is simply the sum of the spectral analytical densities at that wavelength. This additivity of spectral densities does not hold, however, for wide bandpass filters but only for very narrow bandpass filters. For example Fig. A-4 illustrates the spectral density distributions of three different red filters, each of which was used to measure the densities on a series of patches on a cyan strip and a magenta strip, and then to measure the densities of the same patches with the two strips superimposed.

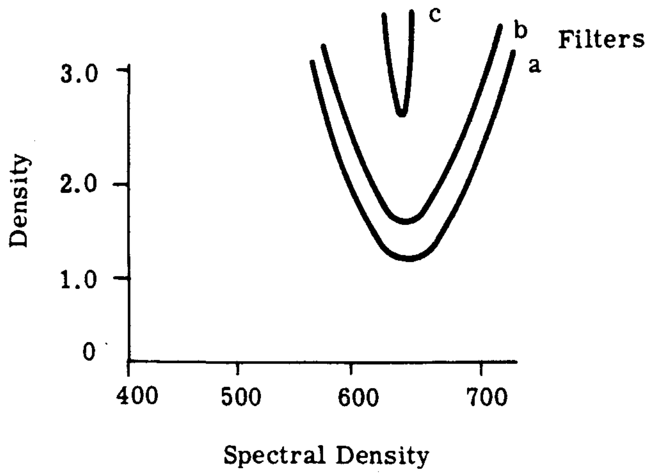


Fig. A-4 — Spectral density distributions of three different red filters

The next series of figures (Fig. A-5) compares the sum of the individually measured densities against the deviation from these densities as measured when the strips were superimposed. Only filter C (the narrow bandpass filter) approaches the ideal of no deviation between predicted (or sum) and actually measured integral spectral density.

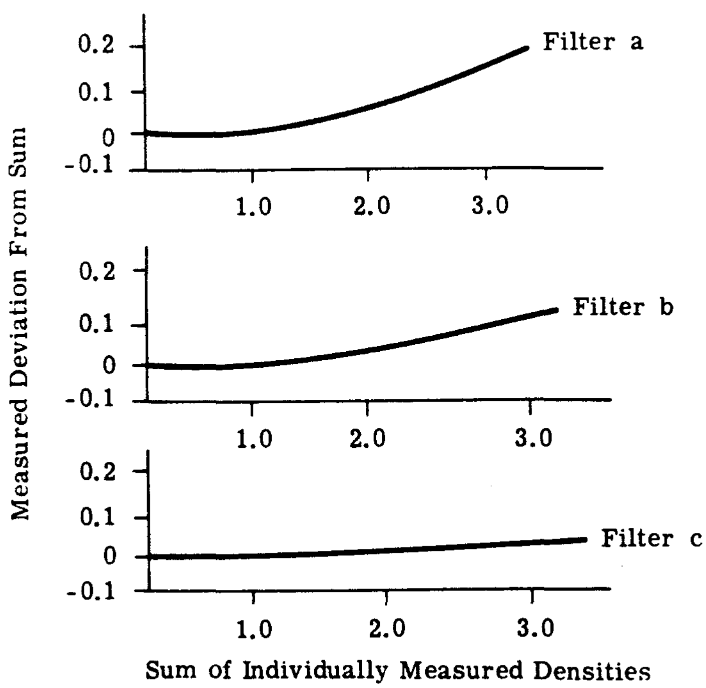


Fig. A-5 — Sum of individually measured densities versus the deviation from these densities when the strips were superimposed

If the new values of D_r, D_g, and D_b are measured or known, and the coefficients B_m, G_y, etc., are also known (from the previous table) then the above equation can be solved for c', m', and y' by matrix algebra. As an example, using the previous dye set and substituting in the above equations we obtain:

$$D_r = c' + 0.059m' + 0.013y'$$

$$D_g = 0.220c' + m' + 0.048y'$$

$$D_b = 0.254c' + 0.154m' + y'$$

Solving the above equations by matrix algebra allows the determination for any new set of integral spectral densities of the amount of each individual color former (i.e., the spectral analytical densities), the above equations become:

$$c' = 1.015D_r - 0.058D_g - 0.010D_b$$

$$m' = -0.213D_r + 1.019D_g - 0.046D_b$$

$$y' = -0.225D_r - 0.142D_g + 1.010D_b$$

The determination of the equivalent neutral densities (END) from the integral spectral densities is equally straightforward. A sample of the color film is exposed to produce a neutral.* The integral spectral densities of this neutral are determined, and using the above equations, the spectral analytical densities are calculated. By definition the END of each of the dye layers forming the neutral is equal to the luminous density of the neutral, regardless of the spectral analytical density of the dye layers. As an example consider a sample exposed to produce a neutral image with a luminous density of 1.0. The END of the cyan, magenta, and yellow layers is by definition 1.0. Even though the spectral analytical densities in all probability will be different, say for this example:

$$c' = 1.052$$

$$m' = 0.751$$

$$y' = 0.826$$

6. RELATIONSHIPS BETWEEN INTEGRAL AND ANALYTICAL DENSITIES

As has already been mentioned, the images in a color film are a result of the separate actions of the three dyes, and the integral and analytical densities are both a measurement of this action by the dyes. Because of the fact that both measurements (i.e., integral and analytical) are a

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* The exposure of a piece of color film to produce a neutral is not always simple. However, by definition for the purposes of determining the END's of color dye layers, a neutral exposure is commonly accepted as the exposure of the color film to a neutral wedge (such as type 3 carbon) with the colorant of illumination the film is intended to be used with (such as daylight, tungsten, flash, etc.)

measure of the action of the dyes, and since the dyes follow the log-D law, it follows that there is a correlation between the two types of density measurement.

Curve s of Fig. A-6 represents the integral spectral densities of an image consisting of three dyes. An increase or decrease in the amount on any one of the dyes in this image would result in a corresponding increase or decrease in density at all wavelengths. The combined density of the three dyes at any one wavelength does not, therefore, indicate the extent to which any one of the dyes contributes to this density, unless the spectral absorption characteristics of the dyes are known. If these characteristics are known, the extent to which each dye contributes to the integral spectral density measurement can be determined.

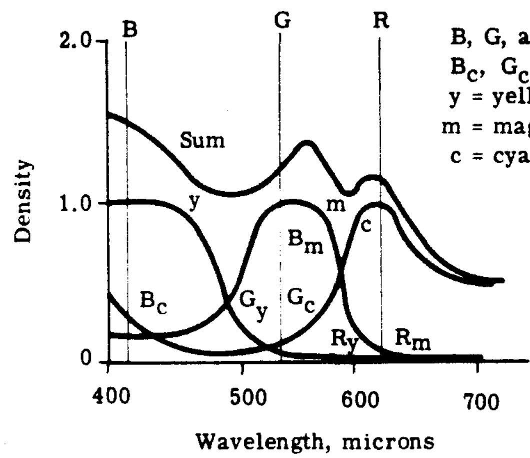

Fig. A-6 — Integral spectral densities of an image consisting of three dyes

The amounts of the dyes will be specified in terms of the spectral analytical densities c′, m′, and y′. By definition, a unit concentration of dye is when the spectral analytical density is 1.00 at the peak absorption of the dye. The wavelengths are labeled R, G, and B for the cyan, magenta, and yellow dyes respectively. Besides the amount of the primary dye absorption at a given wavelength, the amount of "unwanted" absorptions from the other dyes must also be known. There are six such densities and they are designated as G_c, B_c, B_m, R_m, G_y, and R_y. These densities are noted in Fig. A-6, and their numerical values for the particular dyes illustrated in Fig. A-6 are tabulated below. The letters R, G, and B are used to denote the color of the measuring light. The letters c, m, and y are used to denote the dye layer being measured. On this basis it is evident that R_c, G_m, B_y = 1.00.

Spectral Analytical Densities

Density, millimicrons	(c) Cyan Dye	(m) Magenta Dye	(y) Yellow Dye
(R) 620	1.000	0.059	0.013
(G) 540	0.220	1.000	0.048
(B) 410	0.254	0.154	1.0000

Let us now consider these dyes in amounts which differ from those given in Fig. A-6. For any given amount of cyan dye c′, the density of this dye to red light would be c′, to blue light $B_c c'$, and to green light $G_c c'$. The same relationships hold for the other dyes. The integral spectral densities D_r, D_g, and D_b, to red, green, and blue light respectively, of any combination of these dyes, is simply the sum of the spectral analytical densities contributed by each dye component as shown in the following equations:

$$D_r = c' + R_m m' + R_y y'$$

$$D_g = G_c c' + m' + G_y y'$$

$$D_b = B_c c' + B_m m' + y'$$

The END of each layer (c, m, y) is thus related to the analytical spectral density by the equations:

$$\text{END's} \begin{cases} c = \left(\frac{1}{1.052}\right) c' = 0.951c' \\ m = \left(\frac{1}{0.751}\right) m' = 1.332m' \\ y = \left(\frac{1}{0.826}\right) y' = 1.211y' \end{cases}$$

By combining the above relationships between END and ASD with the equations for the determination of analytical spectral density (ASD) from integral spectral density, one can solve directly for the END of a dye layer from the integral spectral density. Thus:

$$c' = 1.015D_r - 0.058D_g - 0.010D_b$$

$$m' = 0.213D_r + 1.019D_g - 0.046D_b$$

$$y' = 0.225D_r - 0.142D_g + 1.010D_b$$

From the END equations above:

$$c' = \frac{c}{0.951}$$

$$m' = \frac{m}{1.322}$$

$$y' = \frac{y}{1.211}$$

Substituting c/0.951, m/1.332, and y/1.211 for c′, m′, and y′ respectively, we obtain:

$$\text{END's} \begin{cases} c = 0.965D_r - 0.055D_g - 0.010D_b \\ m = -0.284D_r + 1.357D_g - 0.061D_b \\ y = -0.272D_r - 0.172D_g + 1.223D_b \end{cases}$$

Thus, to obtain the END's of any combination of the above set of color formers, it is only required to measure the integral spectral density. Once the above equations are established there is no need to recompute them for the same color film, as long as the type of dye used remains the same.

7. REFERENCES

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3. Mees, C. E. K., "The Theory of the Photographic Process," MacMillan Co., New York, 1954.