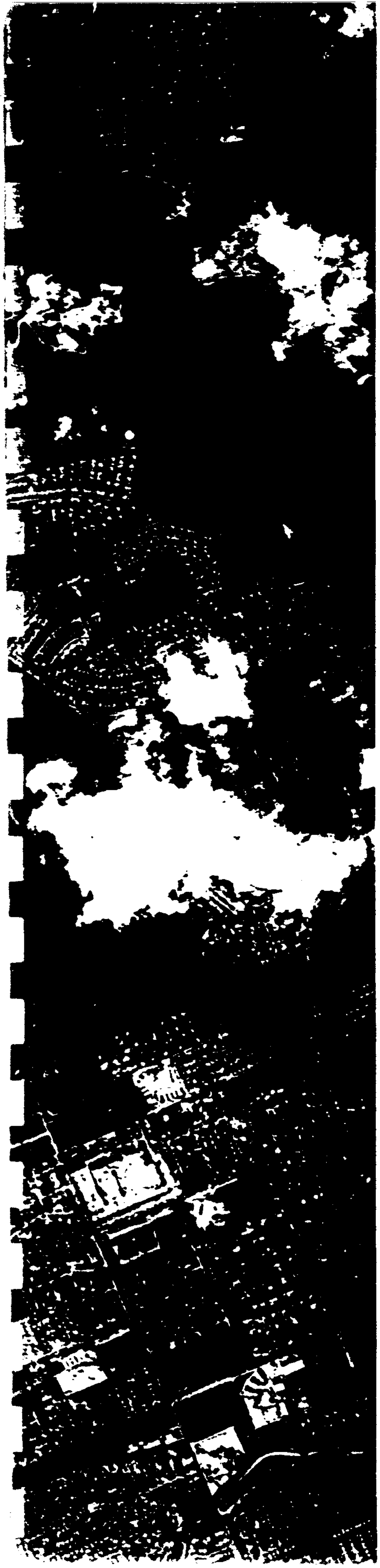

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EKIT REPORT NUMBER 13

EVALUATION OF A POLARIZING FILTER IN HIGH ALTITUDE PHOTOGRAPHY

28 AUGUST 1967

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APPROVED BY

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CONTENTS

FIGURES

1. SUMMARY

This EKIT test was concerned with the effects of a polarizing filter on high altitude black and white photography. The test covered a cloverleaf flight line over Davis-Monthan Air Force Base in Arizona. The polarizing filters were set so that many combinations of flight line, solar azimuth, and filter orientations could be obtained. The analysis of this photography has led to the verification of recent theoretical studies in atmospheric polarization. In addition, a recommended positioning of the polarizing filter has been implemented to obtain best use of the filter.

The analysis of this photography brought about the following conclusions.

CONCLUSIONS

1. The atmospheric hazelight is, as recent theoretical studies have indicated, polarized.
2. A polarizer, orientated in the proper direction, can significantly increase the image contrast at low solar altitudes.
3. The greatest effect of polarizer filters is with the camera that "looks" toward the sun.
4. With pan scanning photography from a vehicle flying perpendicular to the solar azimuth, there will be significant density difference across the format length.
5. No evidence of a decrease in specular reflection was found in the test.
6. There is no significant loss in image quality with the use of a polarizer in this test.
7. The filter factor with maximum polarization is 6.

2. TEST PLAN

EKIT flight test no. 10 consisted of two flights with the 112B Camera System in a high flying aircraft. This section deals with the camera system itself, the modifications that were required for this test, and the flight lines that were used.

2.1 112B CAMERA SYSTEM

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 numbers, 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.

2.2 SCOPE OF THE TEST

Two questions were asked before this test was run. First, since some types of specular reflections are polarized, could a polarizing filter reduce them to the extent that the bothersome "ballooning" of reflections from aircraft wings would be improved? Second, if the atmosphere itself is polarized, could the use of a polarizing filter reduce the polarized component of the hazelight to a significant degree?

Two flights were required in order to successfully complete this test. The first flight [redacted] 11 August 1966) had a late start and the resulting photography was taken at a solar altitude above 63 degrees. This flight (unlike the following one) used both a Wratten no. 21 and a polarizing filter together. The resulting photographs with both filters used simultaneously at the high altitude showed no significant effect of any kind.

The second flight [redacted] 26 July 1967) was flown at a lower solar altitude. This flight was started very early in the morning, and the photography over the prime target area (Davis-Monthan Air Force Base, Tuscon, Arizonia) was taken at solar altitudes of 20 to 30 degrees. This area was chosen so that there would be a sufficient number of aircraft in the imagery to find cases of improved specular reflection. (This is the storage area of several hundred B-47's as well as many other types of aircraft.) The mission then continued to Los Angeles although it was cloudy and no useful photography was obtained.

2.3 CAMERA MODIFICATIONS

No camera modifications could be made to the 112B System that were not compatible with the normal operational mode of the KH-4B System. However, changes in the 112B System that would prove a specific technical point for use in the KH-4B System could be made. This was the case for the polarization test. A split filter arrangement was incorporated in order to obtain the maximum amount of information from one flight. The polarizer filter was incorporated on the aft-looking unit with the axis of polarization orientated in both directions. The forward-looking camera had the polarizer orientated in one direction over half of the slit and the Wratten no. 21 filter over the other half. With mission photography, the polarizing filter, if used, will be orientated in the direction that would give the best results the majority of the time.

2.4 FLIGHT PLAN DETAILS

Table 2-1 includes the specific camera settings used in the second polarizing flight. The flight lines are illustrated in Fig. 2-1.

Table 2-1 — Specific Camera Information for [redacted]

	I7 Forward-Looking Unit	I8 Aft-Looking Unit
Slit width	0.075 inch	0.075 inch
Exposure time	1/250 second	1/250 second
f/no.	3.5	3.5
Film	3404	3404
Filters	Wratten no. 21/Polarizer→	Polarizer→/Polarizer↑

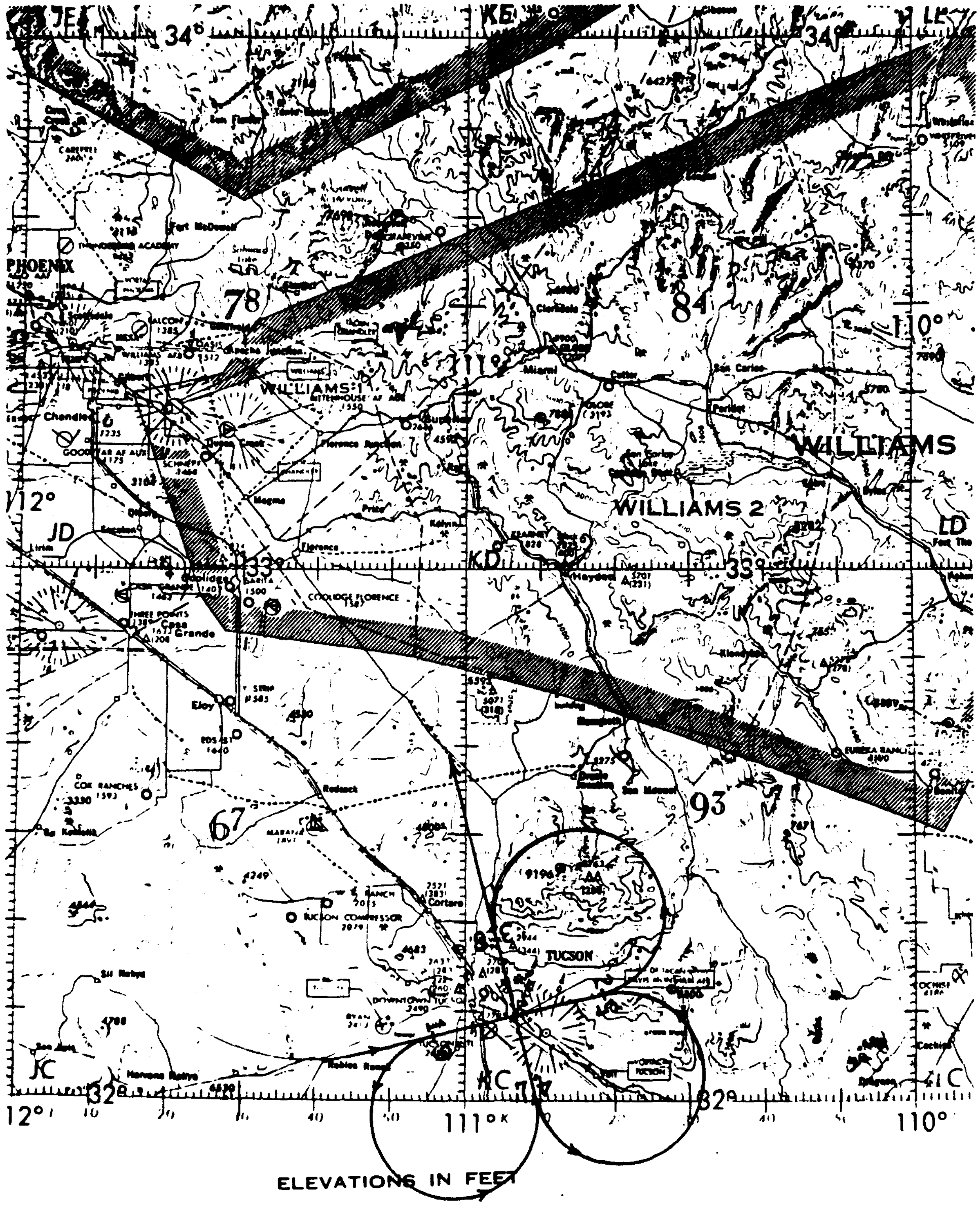


Fig. 2-1 — Flight line used in the [redacted] polarization test

3. POLARIZATION IN AEROSPACE PHOTOGRAPHY

The light, both image forming and nonimage forming, which a reconnaissance camera sees looking down on the earth from above the atmosphere is polarized to a greater or lesser degree. This polarization is basically the result of two naturally occurring phenomena. The first is due to the polarization that results from the reflection of energy from a surface, and the second is the result of scattering in a molecular environment. The fact that the energy reaching the aerospace camera is partially polarized suggests a possible means of enhancing image quality by taking advantage of this phenomenon. This might be accomplished by incorporating a polarizing filter in the camera system, oriented in such a direction as to filter out the unwanted polarized energy, and thereby increase image contrast to obtain better photography.

Electromagnetic radiation is transmitted by a process exhibiting both particle-like and wave-like behavior. Since the concept of energy particles (photons) traveling in a straight line is inapplicable to the process involved in the polarization of light, only the wave-like behavior of light shall be considered.

Water ripples, as seen from above, spread circular disturbances of the water surface. From the side, they are seen as waves in which the water moves in a direction at right angles, transverse, to the wave travel (see Fig. 3-1). Light waves behave in a like manner.

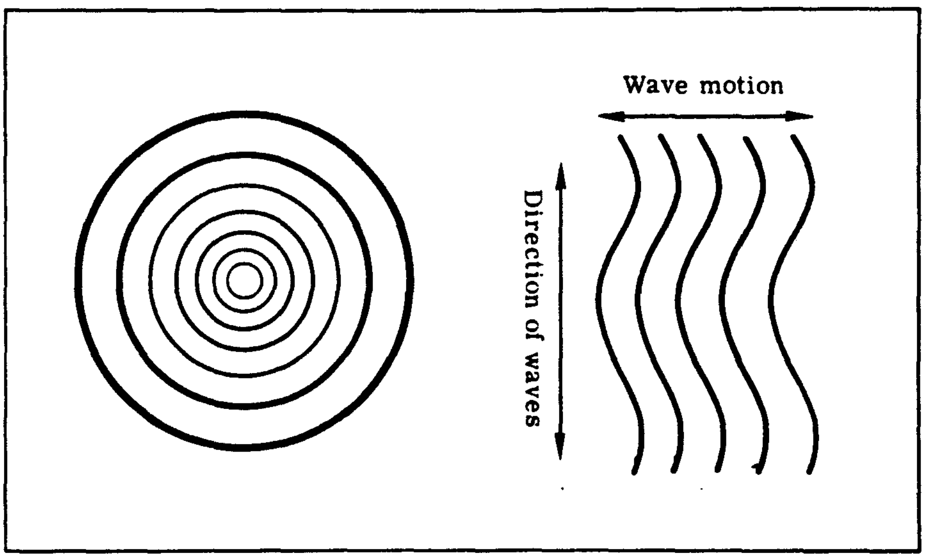


Fig. 3-1 — Water wave ripple patterns

If a length of rope, which is fastened at one end, is agitated by hand in a to-and-fro motion crosswise to itself, a wave travels along it lengthwise. To emphasize the transverse nature of the wave, imagine a knot tied anywhere in the rope. As the wave travels along the rope, the knot, which obviously cannot move lengthwise, oscillates or vibrates in a to-and-fro motion sidewise. A light wave possesses a similar crosswise or transverse vibration which has both an electric and magnetic character.

Ordinary light radiation such as that received from the sun or incandescent lamps consists of a complex mixture of vibrations lying in all possible directions crosswise to the line of travel. Some understanding of the complexity of the wave motion can be gained by returning to the analogy of the rope. If the rope is shaken in a random fashion (horizontally, vertically, and all angles in between), a complex wave motion can be seen to travel along the rope.

Any light in which the arrangement of vibrations is in all possible direction perpendicular to the direction of travel is said to be unpolarized (see Fig. 3-2).

If the vibrations, for one cause or another, are in one direction the light is linearly polarized (see Fig. 3-3).

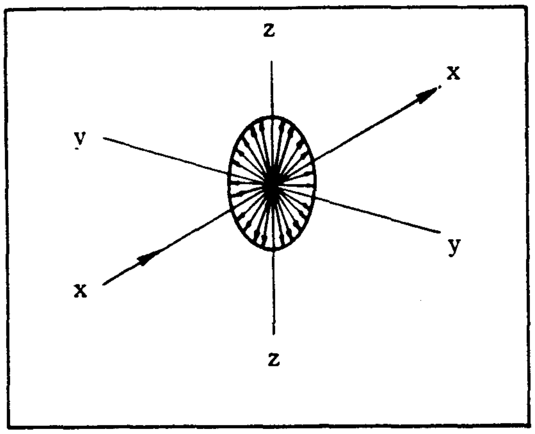


Fig. 3-2 — Natural (unpolarized) light

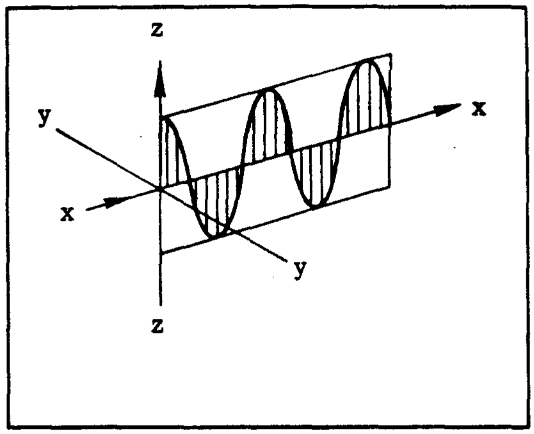


Fig. 3-3 — Single wave vibrating in x-z plane and propagating in the x direction

A beam of polarized light is usually described in terms of what might be called the pattern of vibration. To explain this point, let us assume that polarized light has the property of cutting paper. By passing polarized light through paper, we would find three types of holes: a thin narrow slit, a circular, and an elliptical hole. The light making the narrow slit is said to be linearly polarized, that making the circular hole is regarded as circular polarization, and the elliptical hole, elliptical polarization.

Of the three types of polarization that occur (linear, circular, and elliptical), linear is the only one of interest in the aerial photographic case.

When light reflects obliquely from a surface it becomes linearly polarized in a plane parallel to the reflecting surface. The degree of polarization depends upon the angle of incidence and the refraction index of the reflecting surface. The angle at which the degree of polarization is 100 percent is defined as the polarizing or Brewster's angle. For ordinary window glass, the maximum occurs at 32 degrees to the reflecting surface. Surfaces of nondielectric materials (principally polished metals) have little plane polarizing effect. Diffusing surfaces which present no specular reflection do not polarize. However, most surfaces do reflect linearly polarized "glare light." Other factors affecting the degree of polarization of the reflected energy include the texture of the surface (coarse or smooth), the color of the surface, and the reflectance, absorption, and translucent characteristics of the reflecting materials. In general, low reflectance dielectric materials polarize light to a higher degree than high reflectance materials, and the degree of polarization increases with increasing angles of incidence.

In clear weather, the earth's atmosphere acts as a vast scattering-type polarizer and causes the shorter wavelength light (blue and ultraviolet) to be partially polarized. This polarization is asymmetric and the degree is dependent on the position of observation relative to the direction of primary radiation. Fig. 3-4 illustrates the principle involved in atmospheric scattering. Let us consider a nearly horizontal sun's ray B, shown in this figure. When the ray strikes a certain molecule M, it causes transverse vibrations in the electronic structure of the molecule, and these in turn produce secondary waves traveling in all directions. An observer off to one side viewing the transverse, horizontal ray S_h, will receive only a vertical vibration. Any horizontal vibration that was perpendicular to his line of sight would be parallel to the primary ray B; but B contains no longitudinal vibration (according to electromagnetic theory) and, hence, cannot produce any such vibration. Thus, ray S_h is polarized linearly and vertically. Likewise an observer directly above or below molecule M can receive light of only a single vibrational direction, namely, the direction that is perpendicular both to the primary ray and to his line of sight.

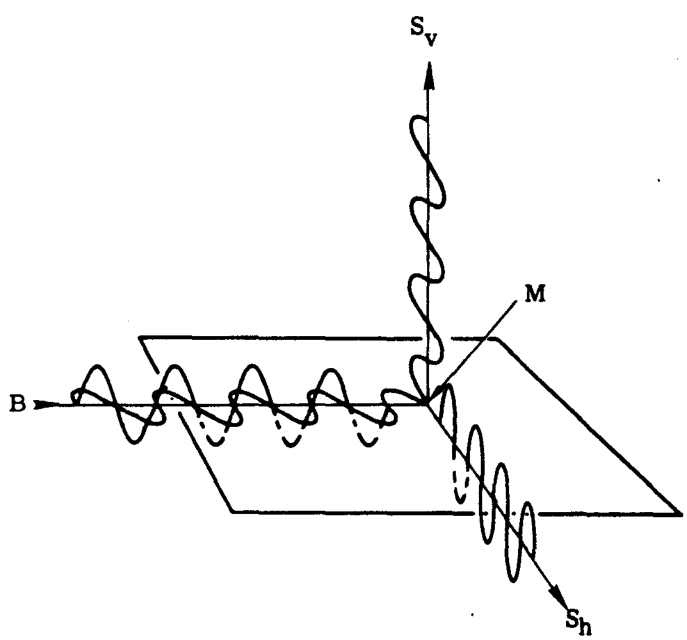


Fig. 3-4 — Pattern of rays S_h and S_v scattered at 90 degrees by air molecule M struck by a horizontal unpolarized beam B (These rays are highly polarized.)

Thus, at 90 degrees to the incident beam, this light is completely polarized in a direction perpendicular to the plane formed by the incident and scattered rays. At other scattering angles, this light is less polarized, and is unpolarized for scattering angles of 0 and 180 degrees. Mie (aerosol) scattering is more weakly wavelength dependent and produces only slight polarization at any angle.

The degree to which hazelight is polarized depends upon the relative amounts of light from these two sources. Other factors being equal, blue hazelight is more highly polarized than red because it arises primarily from Rayleigh scattering. The haze from maritime tropical air is less polarized than that from continental polar air because of the greater proportion of Mie scattering in the former.

Hazelight arises not only from directly scattered sunlight, but also from light scattered after being reflected from the ground and clouds. Most studies consider this to be unpolarized, diffuse light. Most of the ground light haze entering the camera in near vertical photography is forward scattered, and thus, relatively unpolarized.

When the average albedo of the scene is high, the more polarized Rayleigh scattered light, is diluted, and the percentage of polarization is reduced.

The hazelight which reduces object-background contrast can often be reduced by the use of a polarizing filter (analyzer) in the camera system. To the degree that this unwanted light is plane polarized, it can be eliminated by an analyzer in the proper orientation. The amount of polarization depends upon many factors, such as the sun's zenith angle, the target's nadir angle and azimuth, the composition and vertical structure of the atmosphere, and the overall albedo of the scene below. Most of the literature on this subject is based upon theoretical models; few experimental results are now available.

Though detailed predications may require sophisticated models and tedious calculations, the gross features of hazelight polarization are straightforward. In this discussion, the physical processes that generate haze have been necessarily oversimplified. To reduce the scope of the discussion, only near vertical photography has been considered.

The preceding discussion provides several operational considerations for the use of analyzers in near vertical reconnaissance photography. When the sun is directly over the camera, a polarizing filter is useless because the hazelight is unpolarized; however, if the sun is somewhat below the zenith, substantial gains in contrast are possible. Over areas of high albedo, such as snowfields, the analyzer is much less useful than over darker regions like forests. Finally, the use of a haze cutting filter eliminates much of the polarized light, thereby decreasing the marginal utility of the analyzer.

Certain peculiar conditions may have some bearing on the use of polarizing filters. Large homogeneous areas, such as the Sahara desert, under oblique illumination reflect polarized light even in the vertical direction. An analyzer would reduce the hazelight, along with the target object's background light. This might reduce the visibility of a dark object. A specific target under certain conditions of illumination and observation will reflect highly polarized light. In this case an analyzer might reduce the visibility of a bright target.

From operational considerations, if there is indeed an advantage in using a polarizing filter, the KH-4B System is ideal for its employment. Although the planes of maximum polarization will be different for the reflected and scattered light, in both cases the majority of the polarized energy will be linearly polarized horizontal to the earth's surface. Furthermore, the maximum will occur near the sun's vertical, i.e., the plane containing the sun, object, and camera. The KH-4B satellite nominally flies a near noon, basically north-south polar orbit. The cameras, though inclined 15 degrees plus and minus from nadir, scan across the line of flight. As such, they are looking directly into or away from the sun in its vertical position where the maximum polarization effects occur.

Two recent articles on this effect by Carlson* and Fraser† give a very good description of the polarization effects of the atmosphere from a strictly theoretical point of view. A good reference book on this subject has been written by Shurcliff and Ballard.‡

* Carlson, Effects of Reflection Properties of Natural Surfaces in Aerial Reconnaissance, Appl. Opt., 5:905 (1966).

† Fraser, Apparent Contrast of Objects on the Earth's Surface as Seen From Above the Earth's Atmosphere, JOSA, 54:289 (1964).

‡ Shurcliff, W. A., Ballard, S. S., "Polarized Light," Van Nostrand, Princeton, New Jersey, 1964.

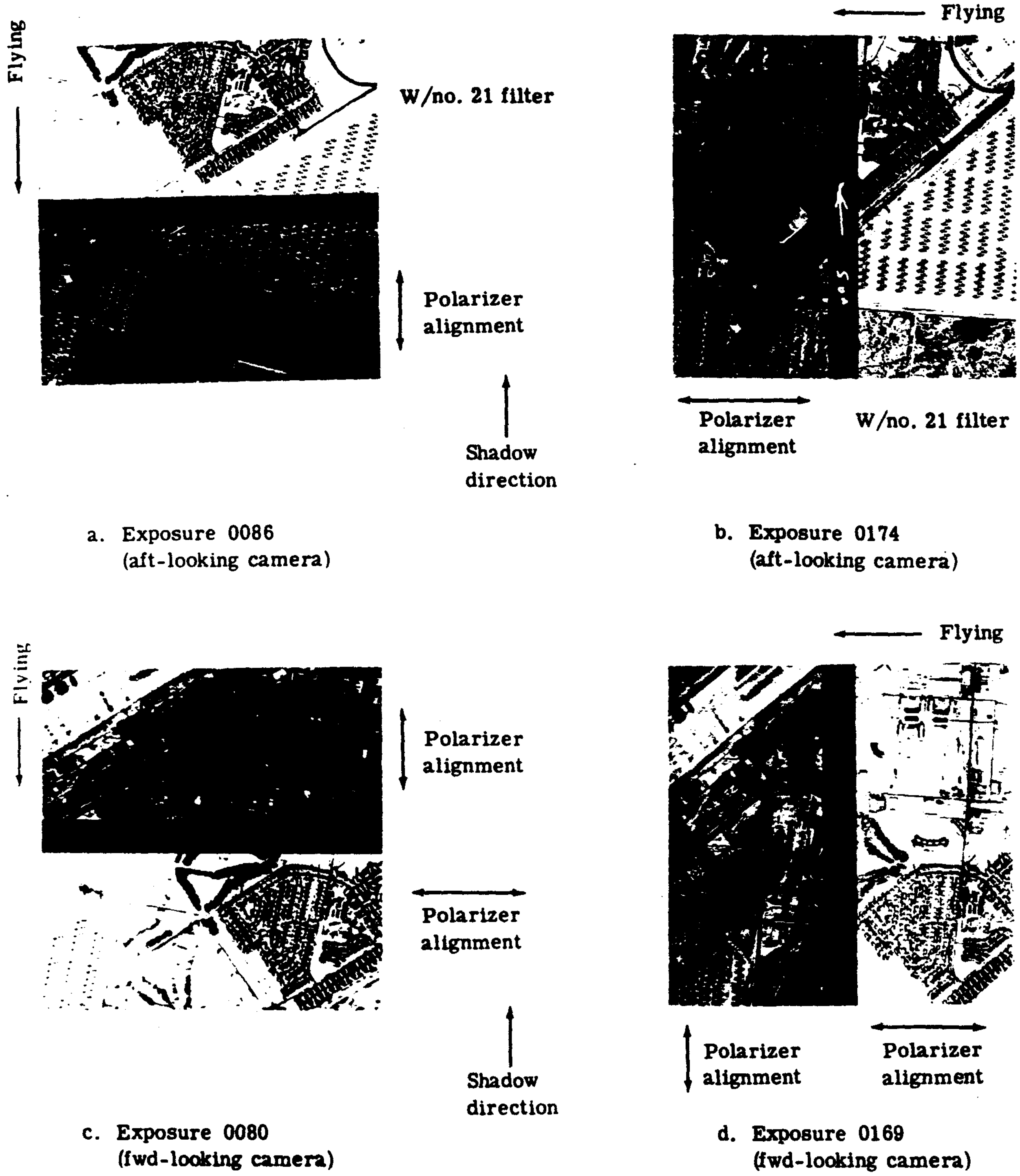
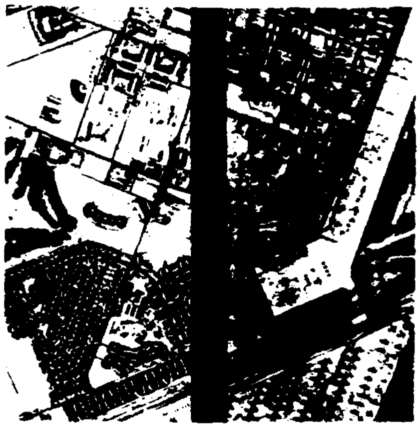
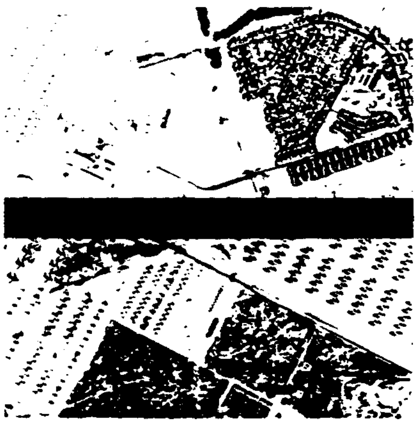


Fig. 4-1 — Contact prints of the same ground area at the center of the cloverleaf flight pattern

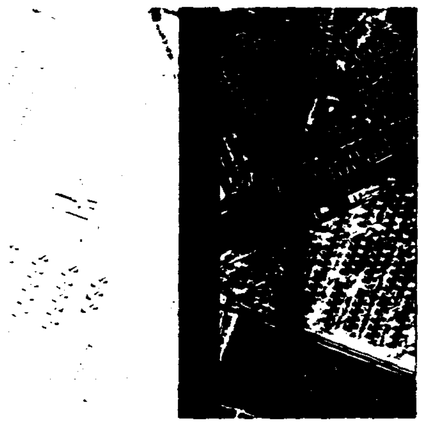
e. Exposure 0273
(aft-looking camera)



f. Exposure 0353
(aft-looking camera)



g. Exposure 0267
(fwd-looking camera)



h. Exposure 0347
(fwd-looking camera)

Fig. 4-1 — Contact prints of the same ground area at the center of the cloverleaf flight pattern (Cont.)

to the first one. In this case, the side that has previously effectively reduced the polarized haze [in Fig. 4-1(c), the side with the timing pipes] did not work because its axis became perpendicular to the solar azimuth. Note that the timing pips on the right side of Fig. 4-1(d) are not very apparent because the image is lighter. Interestingly enough, the other side of Fig. 4-1(d) has had the full effect of the polarization filter and its axis of polarization is also in the plane of the solar azimuth. This print was made, as were the others in this series, from the center of the frame. The discussion of this image will be resumed after an explanation of Fig. 4-1(f).

Fig. 4-1(f) was obtained from the forward-camera when the aircraft was flying away from the sun. on a reciprocal course from that from which Fig. 4-1(c) was acquired. Note that both sides are light, indicating that neither orientation of the polarization filter had a beneficial effect. Even the side of the slit that had the axis of polarization orientated parallel to the solar azimuth exhibited had no significant effect. The reason for this is very simple. Even though this is the forward-looking camera, it is acting like the aft-looking camera if it is assumed that the flight direction was toward the sun. When the camera is pointing away from the sun, or toward the antisolar point, a polarizing filter is of no help in reducing the atmospheric hazelight.

Refer again to Fig. 4-1(d) which was partially described above. The previous descriptions applied to that portion of the center of the frame. Since this flight line was made perpendicular to the sun, the scanning for the entire frame extends from the sun to away from the sun. In effect, the left and right ends of the frame are acting as forward and aft cameras and the polarizer's filter efficiency will vary across the frame. This is an undesirable situation since the average density along the frame's length can vary by as much as 0.6.

The final image, Fig. 4-1(h), in the forward-looking series is the same as the second with the exception that the aircraft is flying in the opposite direction. Since its flight line is also perpendicular to the solar azimuth, this frame also has a density variation across the format due to the look angle effect of the polarization filter.

4.3 GENERAL CONCLUSIONS

There is a definite advantage to be gained by the use of polarization filters in photography as long as the camera incorporating the filter is aimed toward the sun. If the polarizing plane is oriented with its axis of polarization parallel to the solar azimuth, the resulting imagery will contain increased contrast with no significant loss in image quality.

However, care must be taken, with pan scanning photography if the aircraft is flying perpendicular to the solar azimuth. Variations in the polarizing filter's effect will cause, in these cases, serious density variations across the format. The polarizer offers no benefit when used on cameras pointing away from the sun.

A filter factor for the HN-38 polarizer was determined when it was positioned for maximum polarization in the 112B System. Objects of various densities were located on both the maximum polarized and Wratten no. 21 negatives. The densities of these objects were determined from both negatives and plotted on the D-log E curve. With sufficient sampling, it was then possible to average the resulting log E differences and obtain a filter factor that indicated the amount of filtration in excess of that of the Wratten no. 21 due to maximum polarization. This factor, as indicated in Fig. 5-5 is multiplied by the filter factor of the Wratten no. 21 which is 2.1, giving the filter factor of 6.0 for the polarizer at maximum polarization. Fig. 5-5 contains the densities of one object as photographed with maximum and minimum polarization (the plateau region of the scan in Fig. 5-2) effect. This new filter factor is valid only when the polarizing axis is set for maximum polarization. At a nonpolarizing axis, the polarizer has a filter factor of 2.94, or rounded, up to 3.0.

5.3 SENSITOMETRIC EFFECTS CONCLUSIONS

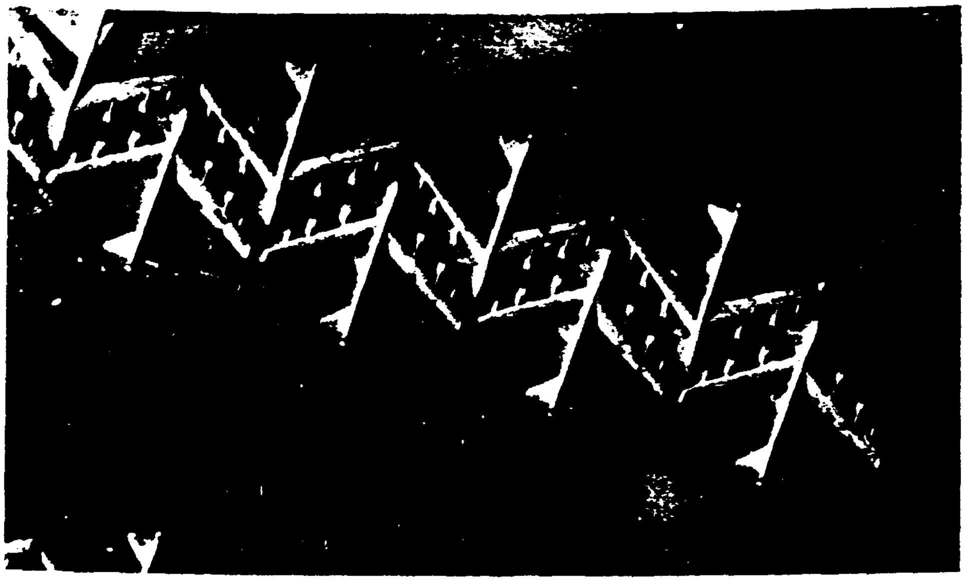
The amount of light removed from the imagery is constant across the entire log exposure range of the sensitometric curve. It is assumed that this is from the polarized component haze-light which is reduced with the full effect of the polarizing filter.

The filter factor has been computed with a laboratory test and in actual practice. There is a considerable difference in the two, the 112B test being more practical. It ranges from 3.0 at minimum effect to 6.0 for maximum polarization.

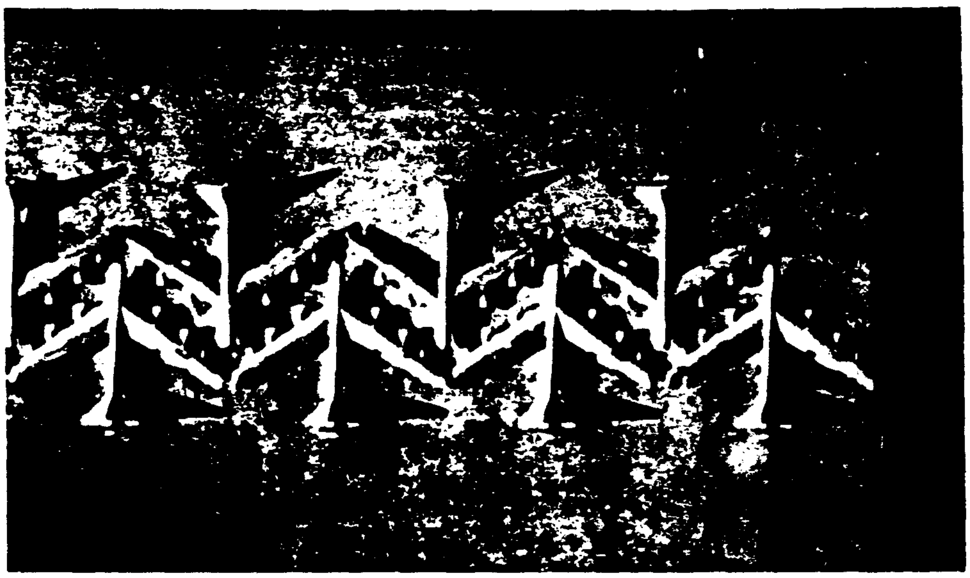
For actual flight tests, when the vehicle is not flying directly into the sun, the filter factor will be between these two values.

a. Polarized

Fig. 5-1 — Aerial photographs of B-52 aircraft



b. Nonpolarized



c. Wratten no. 21 filter

Fig. 5-1 — Aerial photographs of B-52 aircraft (Cont.)

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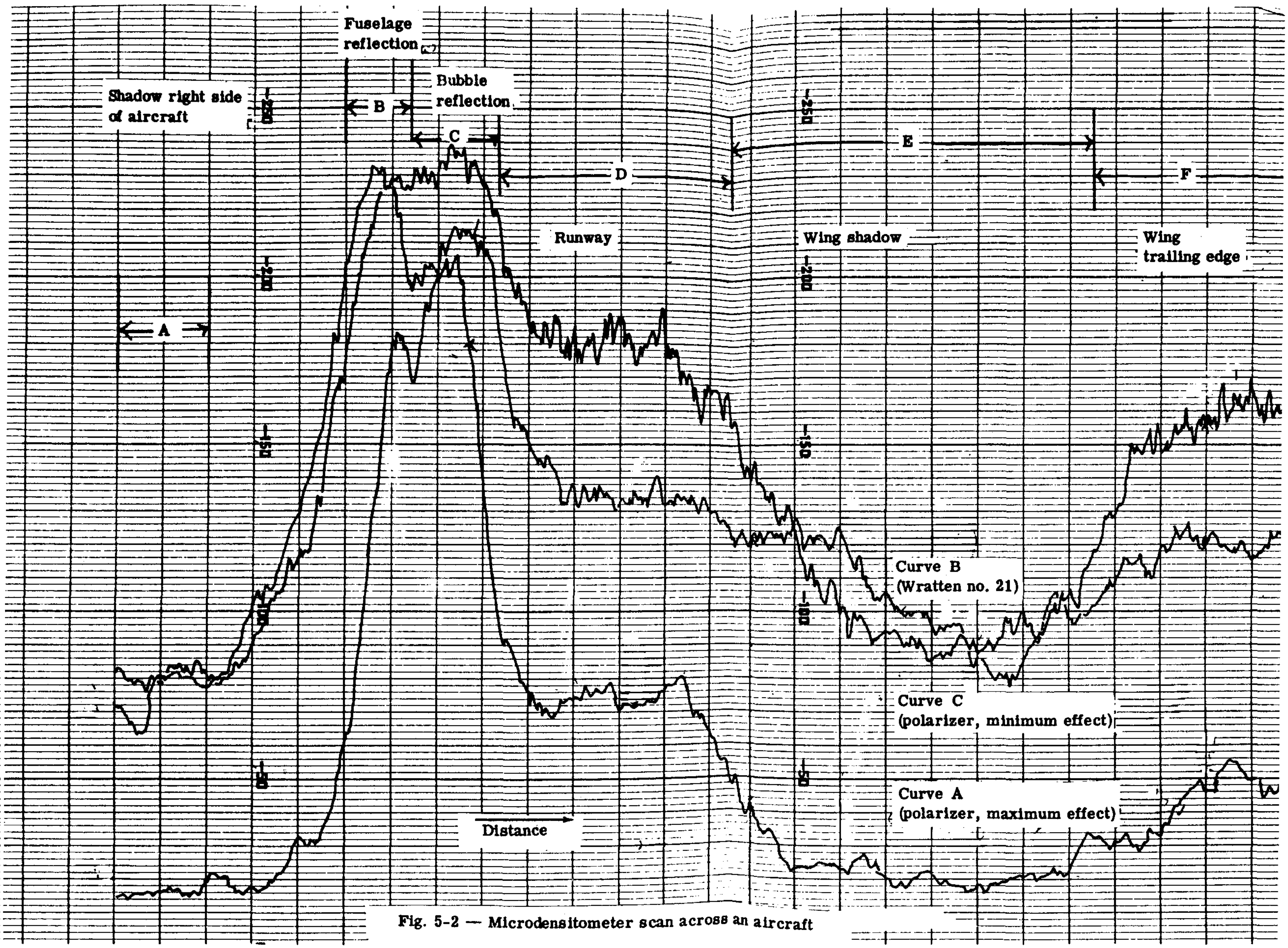

Fig. 5-2 — Microdensitometer scan across an aircraft

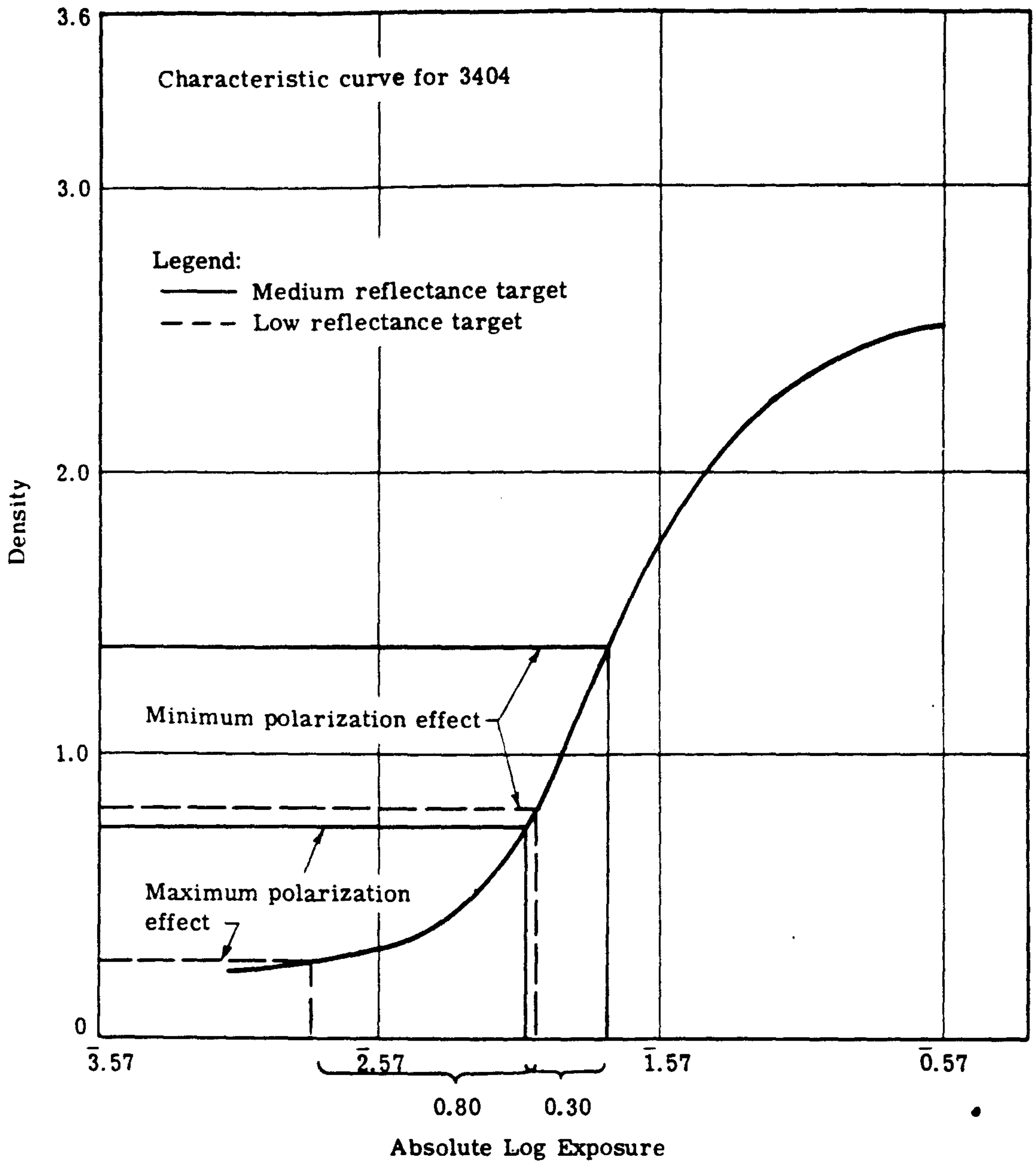

Fig. 5-3 — Effects of maximum polarization on low and medium reflectance objects

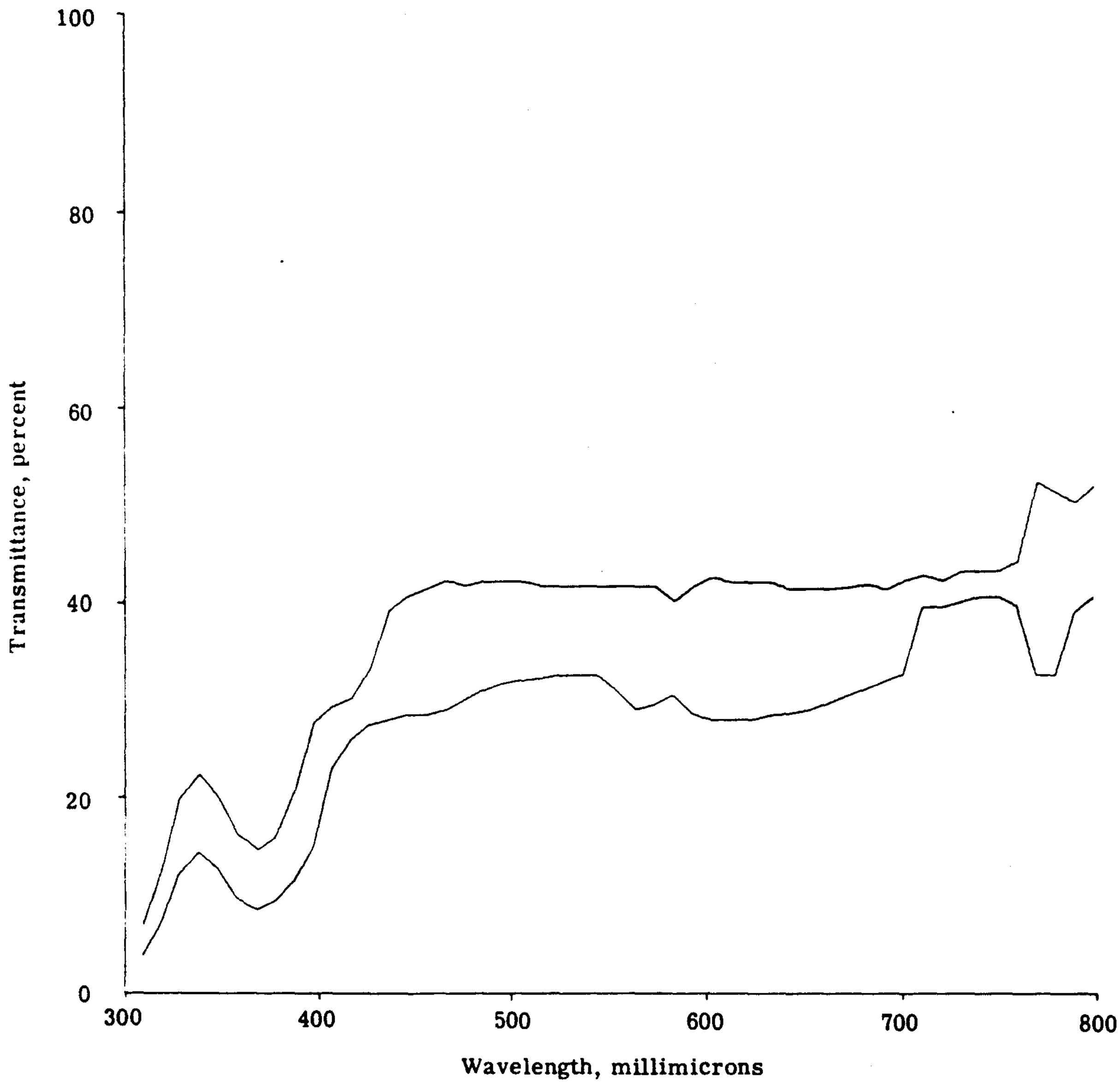

Fig. 5-4 — Spectrophotometer scan of a polarizing filter orientated in two directions (90 degrees to each other) in the spectrophotometer

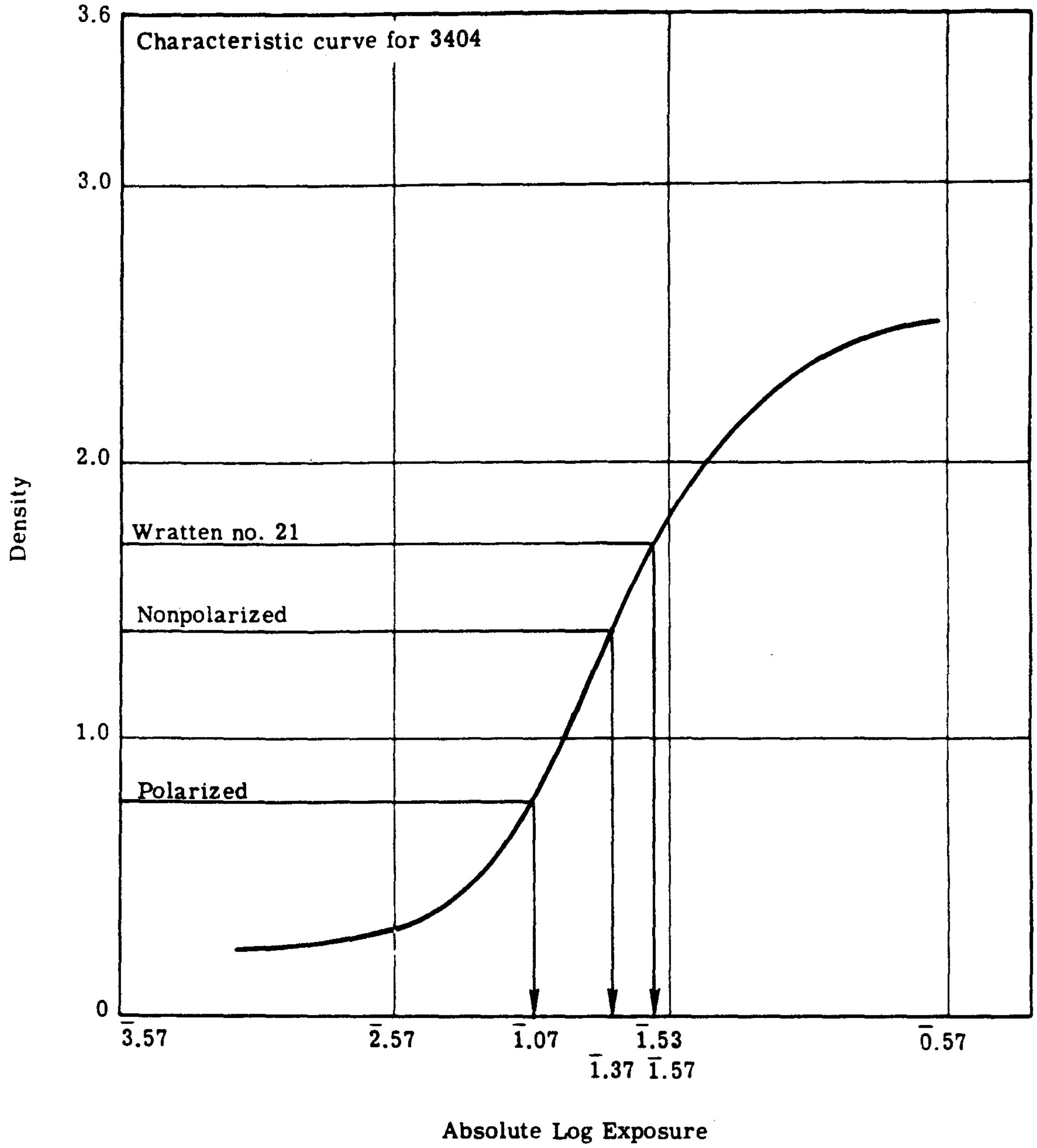

Fig. 5-5 — Filter factor for HN-38 polarizer as determined by log E difference due to maximum polarizing axis and for nonpolarizing axis when compared with the Wratten no. 21 filter

6. KH-4B SYSTEM CONSIDERATIONS

There are basically two factors that should be considered when deciding upon the use of a polarizing filter on mission photography: (1) the image quality degradation, and (2) the beneficial effects on the image contrast. From laboratory tests, a resolution loss of approximately 15 percent has been experienced when a polarizing filter is used in place of the normal Wratten no. 21 filter. It is difficult to explain why the loss is so slight, since the lens is imaging the entire visible spectrum (considerably more of a wavelength region than it is designed for). Part of the reason could be related to the filter's slightly lower transmittance in the blue region (see Fig. 5-5). From the imagery of this test, the polarizing filter appeared to have as high a quality as that of the best Wratten no. 21 photography. For example, the dual engines of the B-47 and B-52's are clearly visible.

The second consideration (can a polarizer help the contrast) is analyzed in the affirmative if the polarizer is orientated in the proper direction. Since current KH-4 photography is almost entirely taken on descending orbits from 70 to 20 degrees North latitude, the forward-looking camera looks toward the sun for almost all of the intelligence gathering photography. The reason for the photography being taken on the descending orbits is that by the nature of the elliptical polar orbit the perigee is around 20 to 40 degrees North latitude. The best place for a polarizing filter would then be on the forward-looking camera with the axis of polarization aligned parallel to the solar azimuth. The polarizing filter will serve no useful function on the aft-looking camera.

However, if the KH-4B photography assumes a more circular orbit, there may not be any reason for always taking descending orbit photography. In this case, the recommended positioning of the polarizer must be reconsidered for it may be needed on either camera, which ever looks into the sun.

POLARIZATION ORIENTATIONS

Although the orientation of the polarizing filter is a critical point for its intended use, its settings work out very conveniently. The filter should be cut out of a larger sheet such that the axis of polarization is parallel to the solar azimuth at the time of the photography. Since the precision (of 1 to 3 degrees per day) causes the local sun time to change during a mission, it is recommended that the polarizer for CR-3 be aligned for the solar azimuth half way through the mission. In this manner, most of the photography will be very close to using the full effort of the polarizing filter. The density will also be quite even across the format of the frame.

The polarizer test is scheduled for CR-3; and CR-3 is currently programmed for a February through April launch. To obtain good test material if the launch slips to April will require photographic acquisition at high northern latitudes (i.e., about 60 degrees North latitude). This means that the polarizer photography will have to be obtained during the most convenient portion of the orbit. Because, then, of the difficulty in polarizer photography, it would seem best to orient the polarizer relative to the solar azimuth at the middle of the missile.

7. CONCLUSIONS

The following conclusions are drawn from this experiment which apply to the KH-4B System. It should be pointed out that these conclusions apply (strictly speaking) to the southwestern part of the United States at a solar altitude of 20 to 30 degrees. It is believed that the basics of these conclusions also apply to Soviet territory when covered at these particular solar altitudes.

1. The atmospheric hazelight is, as recent theoretical studies have indicated, polarized. The most heavily polarized component is in the azimuth and direction of the sun. The antisolar point has the least amount of polarized hazelight.

2. A polarizer, orientated in the proper direction, can significantly increase the image contrast at low solar altitudes. The proper orientation is with the axis of polarization parallel to the solar azimuth. With the orientation perpendicular to the solar azimuth, the polarizer filter serves no useful function.

3. The greatest effect of the polarizing filter is with the camera that "looks" toward the sun. With descending orbital photography, this is the forward-looking camera in the northern latitudes. A polarizing filter on the aft-looking camera will not reduce the atmospheric hazelight.

4. With panoramic scanning photography from a vehicle flying perpendicular to the solar azimuth, there will be a significant density variation along the format length. This will occur if the axis of polarization is, again, parallel to the solar azimuth. With it orientated perpendicular to the solar azimuth, this condition will be eliminated, though there will be no beneficial effect.

5. No evidence of a decrease in specular reflections from aircraft was found in this test. This conclusion applies only to the solar altitude range encompassed in the test, below 20 to 30 degrees. It also agrees with polarization theory that indicates reflections from metalic surfaces are not polarized.

6. There is no significant loss in image quality with the use of a polarizer. A laboratory test indicates that the resolution loss would be on the order of 15 percent with a polarizer over that of the Wratten no. 21 filter, however, the analysis of the flight photography shows no such loss in quality.

7. The filter factor with maximum polarization is approximately 6. The factor should be used when the polarizing axis of the polarizer is parallel to the solar azimuth for best exposure correction. Since most of the photography will be obtained at slightly less than the optimum condition (not flying directly into the sun) the filter factor will be somewhat less. It will probably be on the order of 4 to 5 for most mission photographs.