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Color for Metric Photogrammetry

The very slight degradation in resolution of bar targets is more than offset by the higher resolution of natural and cultural features.

(*Abstract on next page*)

INTRODUCTION

THE COAST AND GEODETIC SURVEY has routinely used color aerial photography for analog aerotriangulation, analytic aerotriangulation, and map compilation during the last five years. Color film is presently utilized for approximately 60 percent of its aerial photography. This percentage will increase as laboratory facilities for processing and printing color materials are expanded.

Black and white infrared photography will probably continue to be used for the delineation of the low-water line in the Coast Survey coastal mapping program. Panchromatic emulsions on glass plates will be used for the majority of geodetic point and boundary location work, wherein specific black and white targets are to be precisely located by photogrammetric methods. All other aerotriangulation and map compilation requirements will be fulfilled through the use of color photography.

When the Coast and Geodetic Survey first used color aerial photography nine years ago, the available films were extremely slow and had such low resolution characteristics that very low-altitude photography was required in order to record ground images adequately. Even with this temporary handicap, the additional dimension of color proved to be an invaluable asset which became mandatory for the Coastal Mapping Program. Field edit or field completion of photogrammetrically compiled manuscripts was an extremely costly phase of the mapping program when panchromatic photography was used because it was necessary for a field man to walk along most of the shoreline to clarify and interpret the planimetric detail. The superior interpretability of natural and cultural planimetric detail when color aerial photography was used considerably reduced the amount of time that was formerly spent on this phase.

Between 1958 and 1961, color photography from relatively low altitudes (1,500 to 2,200 meters) was used as a supplement to higher-altitude panchromatic photography—the high-altitude photography being used for aerotriangulation and general map compilation, and low-altitude color being used to photoidentify and locate important chart features such as landmarks, hydrographic survey signal sites, aids to navigation, submerged hazards to navigation, and the delineation of shoal areas.

Each successive year brought new progress and a more promising future for the metric application of color aerial photography. By 1961, color aerial films with higher resolving

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power and greater speed became available. These films proved to be adequate for primary mapping photography and control densification by aerotriangulation in coastal areas at flight altitudes up to 4,500 meters.

Between 1961 and 1963, color emulsions were available only on acetate bases, whereas panchromatic films were available on the more stable polyester and polycarbonate bases. In addition, a color emulsion on glass-plate disapositives was not available, making it necessary to do aerotriangulation and stereoscopic compilation with black-and-white disapositives made from the original color films. Despite these temporary drawbacks, the metric quality of color film was of a total color system which could completely replace the panchromatic system for aerotriangulation and stereoscopic map compilation.

In 1963 color photography was successfully introduced to the Bureau's Airport Survey Program, and used for aerotriangulation where a flight height of approximately 5,500 meters is required to obtain adequate ground coverage with a minimum amount of ground control survey work.

Precision analytic photogrammetry has been developed to the point that, aside from the day-to-day instability of the comparators used to measure coordinates (at most, 2 microns), all errors in aerotriangulation are firmly established to be entirely adequate for constructing maps meeting national accuracy standards when aerotriangulation was performed with first-order stereoplotters and comparators at photographic scales as small as 1/3 of the scale of the published map.

ABSTRACT: *The Coast and Geodetic Survey has been using color photography for aerotriangulation and map compilation during the last five years. Extensive tests have continually been performed during this period to evaluate the metric fidelity of several brands of color film. These tests included: grid exposure studies for the determination of differential film distortion properties and diapositive plate emulsion creep; strip aerotriangulation error propagation studies using true film distortion values applied to fictitious photographic coordinates; airborne image resolution tests; and analytic aerotriangulation accuracy tests using recent color and panchromatic aerial photography taken over the McClure, Ohio, camera calibration test site. The results of these tests indicate no significant difference in the metric stability between the color and the panchromatic film systems.*

The two missing links in the complete integrated color mapping system were provided in 1962 and 1963. First, the direct viewing stereoplotter for map compilation was introduced to the photogrammetric community; then glass disapositives with color emulsions that permitted the preservation of a stable reproduction of the original aerial exposure were developed and marketed. Shortly thereafter, color film became available on the same polyester and polycarbonate base material that is presently used with panchromatic aerial film. During this period the resolving power of aerial color films was also improved to the point of nearly equaling that of the standard panchromatic aerial films for all combinations of natural colors including black-and-white resolution targets. These developments fulfilled the requirements attributable to unknown or uncontrollable errors in the central perspective of the aerial photograph diapositive. During the last five years considerable effort has been expended on the isolation, analysis, and compensation of systematic errors in the aerial photograph.

FILM DISTORTION STUDIES

Film distortion, universally recognized as one of the prime sources of photogrammetric error, was given much attention throughout our program to improve the metric fidelity of the central perspective.[1] The results of this major effort led to the unmistakable conclusion that the color films marketed by the two leading manufacturers are metrically equal and indistinguishable from the relatively stable Plus-X Aerographic panchromatic film on a 0.004-inch polyester base. This conclusion holds for the case where contact diapositives are used in conventional optical-mechanical stereoplotters, as well as the analytic aerotriangulation case where mathematical models for the compensation of film

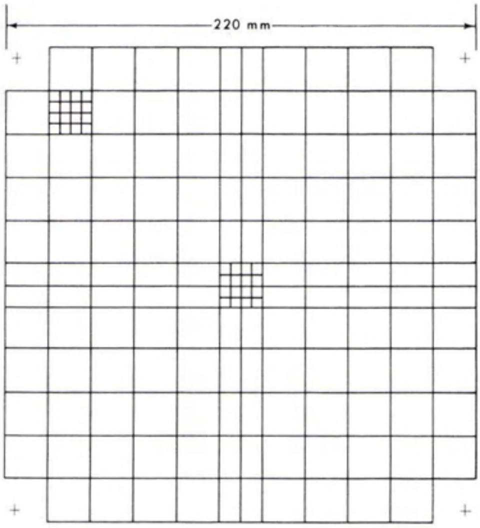

FIG. 1. Calibration grid for film distortion studies.

distortion are defined, depending upon the camera used, through the displacement of four or eight fiducial marks exposed on the photographic format.

Exhaustive film distortion studies were conducted by means of a glass plate which had throughout the photographic format numerous grid intersections whose coordinates were precisely calibrated to a standard error of approximately 1 micron[2] (see Figure 1). This glass grid was contact printed throughout various sample panchromatic and color film rolls, through the use of a vacuum frame. Six exposures of the grid from each sample roll were then transferred to glass diapositives following the normal film negative aging period of six weeks and subsequently measured with a precisely calibrated Mann comparator.

The grid distortion measurement data were initially used to compare the ability of color and panchromatic aerial films to preserve their metric characteristics through the processing phases. Secondly, these data provided the means to test the capabilities of color and panchromatic films to respond to proven techniques of film distorted compensation.

Figure 2A demonstrates the gross film distortion encountered along with effects and effectiveness of various fiducial mark systems and reseau spacings on the ability to recover a grid coordinate at any point within the entire photographic format for each film sample. The results of this test, as shown on the graph, require several explanations and qualification.

The first three values for reseau spacings shown on the abscissa can be correlated with the number of fiducial images used for film distortion compensation. Infinite reseau spacing, or zero reseau marks, simulates the condition of uncompensated film, i.e., film used with analog plotting equipment where the compensation for differential distortion is impossible. The four-corner fiducial mark case is identical to a 22-cm. reseau spacing, and the 11 centimeter reseau very nearly approximates the eight fiducial mark case. A true 11-cm. reseau would require a centrally located mark.

A very important difference exists between optically imaged fiducial marks and reseau grid images within the photograph area. Each fiducial mark is optically projected through a short focal-length lens system by an individual light source thereby producing a high-contrast, high-resolution image on a uniform background. On the other hand, grid spacings less than 11-cm. require the use of a camera reseau in contact with the emulsion or projected either by the camera lens or through the film base. In any case, the multitone terrain on an exposed photograph replaces the high-contrast, high-resolution image on a uniform background that is produced by internally projected fiducial marks and the high-quality grid images used for this laboratory test.

The shaded portion at the left side of the chart indicates the standard-error zone for the measurement of these high-quality projected fiducial marks. The shaded portion to the right of the 6-cm. grid spacing is, in our opinion, a conservative estimate of the standard-error zone for aerial camera reseau image measurement. This limitation is pointed out here to indicate that one apparently cannot take advantage of the small

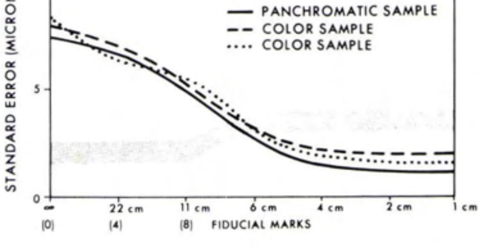

FIG. 2A. Reseau spacing versus standard error of all points.

gain in accuracy which could theoretically be obtained by using reseau spacings of less than 6 m.

From the metric standpoint, the pass-point errors are of prime concern because they are the source of error propagation throughout an aerotriangulation bridge performed in either the analog or analytic mode. Figure 2B demonstrates the standard error of recovery of a point in the most probable pass point areas for each film sample after various types of distortion compensation have been applied.

The data from the grid studies were further utilized to construct three fictitious strips of six aerial photographs with 60 percent endlap for the purpose of observing error propagation caused solely by true differential film distortion and random comparator measuring error. As the grids were contact printed in the laboratory under controlled conditions, any additional propagation of error throughout the simulated strip caused by atmospheric refraction, characteristic camera lens errors, or other unknown external sources of systematic errors, is absent.

Routine Coast and Geodetic Survey analytic aerotriangulation techniques were applied to the simulated strip coordinates for the photogrammetric solution of ground coordinates. Figure 3 shows a typical horizontal and vertical error propagation in the computed ground coordinates at unit scale for each of the three types of film tested. For this particular error-propagation plot, the image coordinates were compensated for film distortion through an eight-fiducial-mark adjustment. Horizontal control points were selected at the midpoints of the ends of the strip and vertical control points at each corner. The selection of this particular array of control permits the propagation of error in a relatively free, unrestrained manner, whereby the photogrammetric bundles are not distorted or deformed to fit other control points spaced throughout the strip. The standard errors of the plate coordinates resulting from the analytic relative orientation phase of the aerotriangulation process were well under 1 micron. Therefore, image displacement caused by film distortion and measuring error was, in fact, transformed into the orientation parameter errors that caused the observed error propagation.

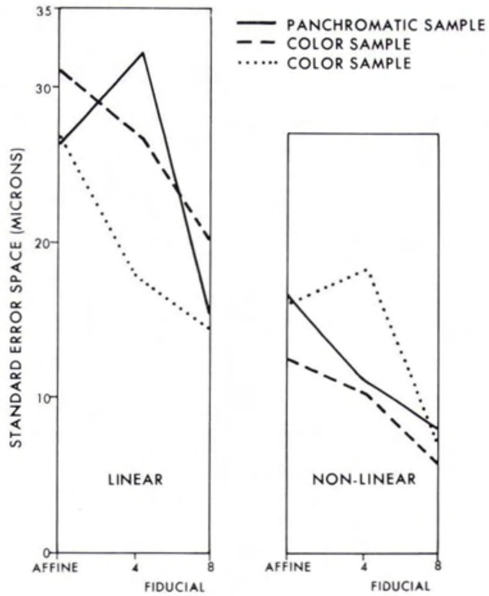

FIG. 3. Standard error of position determined by aerotriangulation applying the film-distortion compensation technique.

No significant difference existed in the error propagation properties of the panchromatic sample and the two color samples used in this test.

Figure 4 shows the resultant three-dimensional standard errors of position for the panchromatic and two color strips after various types of film distortion compensation and techniques for adjustment to ground control.

The results demonstrate: (1) the improvement in accuracy if eight fiducial marks are used to compensate differential film distortion; (2) the merits of a non-linear adjustment of model coordinates to ground control; and (3) the lack of significant difference in photogrammetric accuracy between panchromatic and color photography.

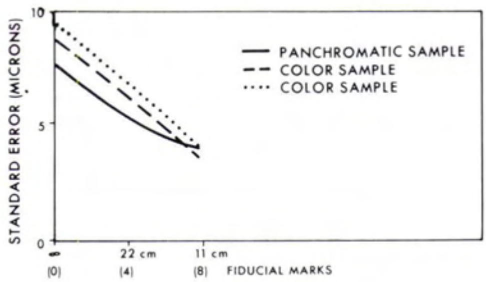

FIG. 2B. Reseau spacing versus standard error of pass points.

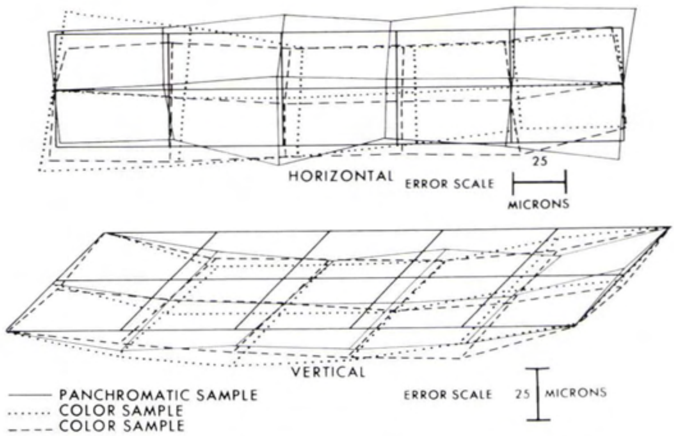

FIG. 4. Error propagation caused by film distortion.

Stability of Color Glass Diapositives

The diapositive printing process was also considered as a possible source of loss of metric fidelity in the color system. Due to the time required to conduct physically a set of coordinate measurements of a plate or stereoscopic model, the work is normally performed on stable glass-plate reproductions of the original exposures. It is, therefore, important that diapositive plates be kept relatively free from image shift throughout the exposure, chemical processing, drying, and measurement phases of their use.

The color glass diapositives now marketed were tested and found to be metrically equal to the standard microflat glass diapositives used in the panchromatic system. The procedures and techniques used for these tests were nearly identical to those described in the previous section for the evaluation of gross film distortion. The standard error of a coordinate after transfer to a color glass diapositive was found to be less than 2 microns. This standard error level is within one's capability to recover a point on panchromatic diapositives if comparator pointing, calibration error, and emulsion creep is considered. It is not surprising that this high metric quality was achieved as the color emulsion is coated on a film base which is subsequently laminated or fastened to the glass by an adhesive during the plate manufacturing process.

Aerial Cameras and Color Photography

Aerial camera lens distortions can be assumed to be negligible when comparing the metric fidelity of panchromatic and color photography. Modern wide-angle camera lenses are now designed for the use of the entire visible spectrum, a quality which is as necessary for high-quality panchromatic photography as it is for color. Three well-known aerial cameras with modern color corrected lenses have been tested with color film to determine the influence of residual chromatic aberration on the metric fidelity of aerial photography taken with panchromatic and color emulsions. Each camera exhibited a slight lack of spectral balance for white objects imaged beyond 40 degrees from the optical axis. However, no geometrical displacement could be detected between images of red, green, blue, gray, or white targets.

It is interesting to note that the order in which the three sensitized color layers are arranged on the film base (blue on top, green in the middle, and red on the bottom) *tends to compensate, rather than contribute to, image displacement caused by chromatic aberration.*

If, in the future, a more thorough laboratory test indicates that significant image displacements occur due to chromatic lens aberration, the condition must be common for both color and panchromatic emulsions. Obviously, the color of the object must be known in order to compensate properly for this type of systematic distortion.

These tests, as well as others designed to determine and establish the optimum size, shape, and reflective characteristics of targets for premarking ground points, verified the importance of using small, symmetrical, medium-contrast targets to avoid metric error caused by image spread which is also a function of photographic exposure. This precaution applies as well to panchromatic photography.

The metric quality of aerial photography is influenced to some degree by the resolving power, or ability, of the photographic emulsion to record fine detail. It has been our experience that the resolution of aerial color film, if used in wide-angle photogrammetric cameras, is nearer to that of panchromatic films than the film manufacturers have indicated in their literature. This may, of course, be attributable to characteristics of the particular wide-angle camera-film combinations used by the Coast and Geodetic Survey flight missions. Recently, variable-altitude color and panchromatic aerial photographs were taken of the color and bar resolution targets at Wright-Patterson Air Force Base. These photographs demonstrated a maximum resolving power of 48 lines per millimeter for color film and 54 lines per millimeter for panchromatic film. After examination of many color aerial photographs of various types of terrain, it is our opinion that the very slight degradation in the resolution of black-and-white repetitive bar targets is more than offset by the higher resolution of a large percentage of natural colors which are more frequent in both man-made and natural cultural features.

Airborne Metric Tests of Color Photography

Two strips of near-vertical color aerial photography were recently taken over the McClure, Ohio, camera test site for a practical study of the metric capabilities of the total color system under operational conditions. Three strips of panchromatic film and three strips of panchromatic glass-plate photography were also taken over the same flight line for use as a basis of comparison.

The Ohio camera test site, originally designed and established as the calibration area for the obsolete nine-lens aerial camera, includes 107 targeted triangulation stations within a five-mile square. Circular white concrete pads, six and eight feet in diameter, mark the control stations which are of first- and second-order accuracy. Second-order level lines provide precise elevations for each station and marker.

The photography was taken with a Wild RC-8 aerial camera equipped with a Universal Aviogon lens and eight fiducial marks. A special glass plate camera back was used in lieu of the camera film magazine for the glass plate exposures. Each flight line consists of a 1:35,000-scale, sixty-percent endlap stereotriplet, the center photograph of which covers a densely controlled four-mile square area containing 85 geodetic control points. Pinpoint exposures with both film and glass plates provided a nearly identical coverage of conjugate photographs in each strip.

Standard processing techniques were used to develop the panchromatic and color film strips. After curing the film negatives for six weeks, each exposure was transferred to a glass diapositive plate. Diapositives were also printed from the glass-plate exposures because the target images on the negatives were too dense for coordinate measurement of the highest precision.

Image coordinate measurements were carried out in the stereo mode on a Zeiss PSK stereocomparator. Previous calibration of this instrument showed little or no X-Y-scale differential or non-orthogonality of the axes. The measured coordinates were then processed through the Coast and Geodetic Survey Coordinate Refinement Computer Program[3] which compensates for systematic errors caused by atmospheric refraction, lens distortion, and film distortion for the film samples.

Photogrammetric ground coordinates for each targeted station were computed from the refined plate coordinates of each stereotriplet by the Coast and Geodetic Survey Block Adjustment Computer Program.[4] A minimum of two horizontal control points and three vertical control points were held in the adjustment thereby permitting a free, unrestrained photogrammetric solution. To eliminate the propagational effects of local errors in the identification of any of the control stations used in the unrestrained solution, a least squares, three-dimensional linear adjustment based on all known control points was made. This final adjustment performed on the photogrammetric block adjustment of the ground coordinates for each strip of each sample tended to *normalize* the results for a more comprehensive comparison and interpretation.

Table 1 shows the standard errors of the plate residuals after block adjustment, and the standard errors of the photogrammetrically determined ground coordinates resulting from each panchromatic film, color film, and glass plate stereotriplet.

The standard errors of plate coordinate residuals cannot be considered as absolute indicators of aerotriangulation precision.

TABLE 1. AEROTRIANGULATION BLOCK ADJUSTMENT STANDARD ERRORS

Sample Strip	*Plate*	*Ground-Horizontal*	*Ground-Vertical*
	microns	meters	meters
Color film-strip #1	1.3	0.223	0.236
2	1.6	0.291	0.298
	microns	meters	meters
Panchromatic film-strip #1	1.7	0.256	0.225
2	1.5	0.233	0.230
3	1.9	0.229	0.457
	microns	meters	meters
Glass plate-strip #1	1.2	0.226	0.166
2	1.1	0.214	0.186
3	1.1	0.215	0.200

The point residual itself reflects the failure of the point to satisfy the collinearity condition. Because the analytic solution is relatively elastic, some of the errors on the plate will be transformed into orientation parameter adjustments which naturally tend to reduce the magnitude of the standard errors. To what degree or magnitude the actual standard errors of plate residuals have been reduced in these block adjustments is unknown.

In addition to a block adjustment of each sample strip, a least-squares resection was performed on the center photograph of each stereotriplet for a further comparison of the metric quality between panchromatic and color aerial film.

Table 2 shows the standard errors of plate residuals after resection of the various center plates. The standard errors of position on the ground are simply the standard errors on the plate multiplied by the photographic scale Although these values do not rigorously define ground position precision, they serve as good approximations as the maximum difference in terrain elevation throughout the entire test area is less than ten feet.

CONCLUSIONS

The superiority of color aerial photography for the accurate interpretation of natural and cultural planimetric detail cannot be challenged.

The results of the film-distortion studies, the color-diapositive stability tests, and the statistics based on the aerotriangulation of color aerial photography over the Ohio test area, have provided concrete evidence that color aerial film is metrically equivalent to panchromatic aerial film.

TABLE 2. AEROTRIANGULATION RESECTION STANDARD ERRORS

Center Exposure		*Plate*	*Ground-Horizontal*
		microns	meters
Color film strip	#1	7.3	0.256
	2	8.1	0.284
		microns	meters
Panchromatic film strip	#1	8.4	0.294
	2	8.5	0.298
	3	9.2	0.322
		microns	meters
Glass-plate strip	#1	6.6	0.231
	2	6.4	0.224
	3	6.5	0.228

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