The New Camera Calibration System at the U. S. Geological Survey

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ABSTRACT: Modern computerized photogrammetric instruments are capable of utilizing both radial and decentering camera calibration parameters which can increase plotting accuracy over that of older analog instrumentation technology from previous decades. Also, recent design improvements in aerial cameras have minimized distortions and increased the resolving power of camera systems, which should improve the performance of the overall photogrammetric process. In concert with these improvements, the Geological Survey has adopted the rigorous mathematical model for camera calibration developed by Duane Brown. An explanation of the Geological Survey's calibration facility and the additional calibration parameters now being provided in the USGS calibration certificate are reviewed.

INTRODUCTION

BEGINNING IN THE LATE 1950s, the U.S. Geological Survey (USGS) calibrated aerial cameras that were to be used by contractors on USGS projects (Bean, 1962). In recognition of this capability existing at the USGS, the responsibility for aerial camera calibration in the U.S. Government, except for the Department of Defense, was transferred from the National Bureau of Standards to the USGS on 1 April 1973 (Tayman, 1974). About this time, the USGS Optical Calibration Laboratory's multicollimator instrument was structurally upgraded and expanded to include a total of 53 collimators. This expansion would permit super-wide angle aerial cameras to be accommodated. The upgraded laboratory was located at Reston, Virginia, where it remains today. The laboratory team performs approximately 100 calibrations every year, and their records show that today's cameras have improved significantly in recent years.

Perhaps the National Aeronautics and Space Administration's Large Format Camera, built by Itek in the early 1980s, set a new standard for cameras with improved lenses and forward motion compensation. Following Itek's lead, the commercial aerial camera manufacturers—Wild Heerbrugg, Carl Zeiss Oberkochen, and Zeiss Jena—have made significant improvements in the performance of their cameras both in resolution and distortion. Table 1 indicates typical improvements over the years.

The techniques and procedures for calibrations at the USGS, including a users guide, have been well documented (Karen, 1968; Tayman, 1978; Tayman, 1984; Tayman and Ziemann, 1984; Tayman *et al.*, 1985). The aerial camera is the instrument that gathers the data necessary for subsequent photogrammetric processes and operations. It can be considered as a surveying instrument of great precision when properly calibrated. The metric characteristics and orientation of critical parts of the camera and their relations to one another must be determined by calibration before the photographic data can be used for precision work. Basically, these characteristics are (1) the focal length of the camera lens, (2) the radial and decentering distortions of the lens, (3) the resolution of the lens-film combination, (4) the position of the principal point with respect to the fiducial marks, and (5) the relative positions and distances between the fiducial marks.

Up to now, the USGS Calibration Laboratory has performed its calibration functions and compiled the report in the format given by Tayman (1984). The importance of quality and precision measurement has always prevailed in the lab, and relatively few changes have been made in the basic concept over the years. Now, in recognition of the improvements being introduced by the camera manufacturers, reduced distortion, increased resolution, forward motion compensation, and even stabilized mounts coupled with the photogrammetrist's capability, by means of computerized instrumentation to utilize the improvements, it is timely to apply a more rigorous theory in modeling the camera's parameters. A more rigorous model of the camera parameters will increase the accuracy obtainable in photogrammetric practice. The new analytical model is based on the projective equations outlined by Schmid (1953). This model for calibrating metric cameras has undergone continuous and significant development since Brown published his rigorous treatment of simultaneous determination of the exterior angular orientation, interior orientation, and symmetric radial lens distortion (Brown, 1956).

The original solution utilized a least-squares adjustment of the measured plate coordinates of stellar images taken with a ballistic camera. The star images were taken in support of the National Satellite Triangulation Program using stellar cameras to photograph the satellite against a background of stars (Case, 1955). Since then, significant advances were made by the introduction of a parameterized model of lens decentering distortion and Brown's (1966) refinement of the Conrady (1919) lens decentering distortion model. The culmination of the analytical camera calibration method was reached when DBA Systems issued a report titled *Advanced Methods for the Calibration of Metric Cameras* (Brown, 1968). Finally, a computer software program, *Simultaneous Multi-Camera Analytical Calibration* (SMAC), was produced under contract to the U.S. Army Engineer Topographic Laboratories, Fort Belvoir, Virginia, by Gyer *et al.* (1970). The software system to be utilized at the USGS and discussed in this paper is a modification of the SMAC Program adapted to the USGS multi-collimator instrument. The SMAC is being modified and installed on an IBM PS/2 Model 70 computer by DBA Systems, Inc. of Melbourne, Florida.

PRESENT SYSTEM'S DATA REDUCTION METHOD

The math model now in use is basically a least-squares version of the photogrammetric resection problem. The plate coordinates of the collimator images are the observations and the collimator directions are the known coordinates. Because the collimator image positions have been perturbed by lens distortions, the measured coordinates will be different from their true positions. In the reduction process the position of the interior perspective center and the orientation of the camera are allowed to adjust to minimize the differences between the observed and true image positions. The result is calibrated focal length, profile of the mean radial distortion, and the coordinates of the principal point. Thirty-three collimator images will appear on the

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calibration plate for a standard 6-inch focal length (152.4 mm) aerial camera, giving a total of 66 observations.

Figure 1 illustrates the geometry of one bank of the USGS multi-collimator instrument. Figure 2 illustrates the distribution of the collimator positions that appear on the plate. Figure 3 illustrates the resolution target and the position reticle that is installed in each collimator.

TABLE 1. TYPICAL IMPROVEMENTS IN AERIAL CAMERAS

Camera Item	1960s	1990s
Resolution (AWAR)*	63 lp/mm	90 lp/mm
Radial Distortion	± 10 μm	± 3 μm

*AWAR is area weighted average resolution measured on a Kodak high resolution (400 lp/mm) micro-flat glass plate.

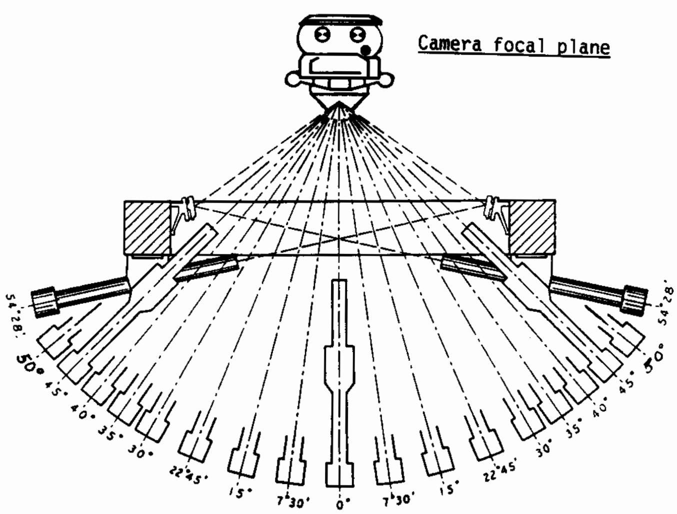

FIG. 1. Schematic diagram of one collimator bank.

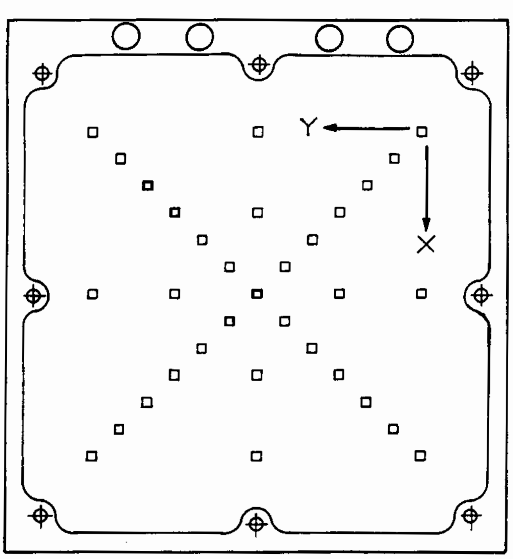

FIG. 2. Target positions that appear on glass plate.

RESECTION EQUATION AS A CALIBRATION MODEL

The well known projective equations of photogrammetry are employed in the present camera calibration system (Karen 1968). They are

$$x - x_p = f\left[\frac{A\lambda + B\mu + C\nu}{D\lambda + E\mu + F\nu}\right] \qquad (1)$$
$$y - y_p = f\left[\frac{A'\lambda + B'\mu + C'\nu}{D\lambda + E\mu + F\nu}\right]$$

in which

x and y are the measured plate coordinates with respect to the photo coordinate system;

x_p, y_p, f are the coordinates of the principal point and focal length of the camera;

$\begin{bmatrix} A\,B\,C \\ A'B'C' \\ D\,E\,F \end{bmatrix}$ = orientation matrix elements which are functions of three independent angles α, ω, κ referred to an arbitrary X, Y, Z frame in object space; and

λ, μ, ν = X, Y, Z direction cosines of rays joining corresponding image and object points.

Summarizing the present method, it should suffice to point out that the data reduction program uses the linearized version of Equation 1 in the least-squares solution of the unknowns. The unknowns are

(x_p, y_p, f): the coordinates of the principal point and focal length of the camera, and

α, ω, κ: the three angles of exterior orientation. α and ω are approximately zero.

The residuals Δx and Δy on each point remaining after the least-squares adjustment are the basis for the radial distortion curve as reported in each USGS calibration report. In the actual reduction, the focal length is slightly adjusted to accommodate for the small shift in unknowns x_p, y_p away from the center of fiducials in the image plane.

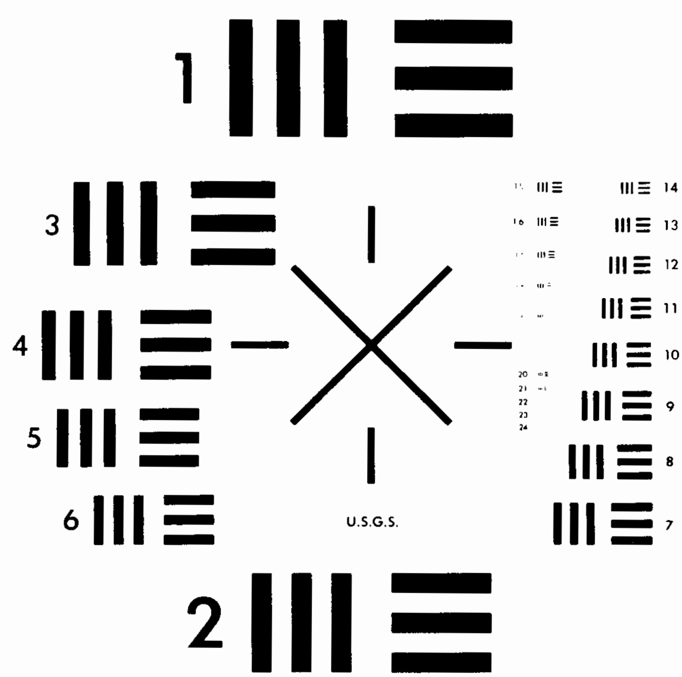

FIG. 3. Reticle/resolution target.

THE NEW ANALYTICAL MODEL WITH RADIAL AND DECENTERING LENS DISTORTION

The new model (Brown, 1966) incorporates Equation 1, the photogrammetric projective equations, and augments them with two parts: symmetric radial distortion and lens decentering distortion. Specifically, the analytical models for radial and decentering distortion are introduced directly into the projective equations. The parameters defining the distortion functions are then solved simultaneously with the projective parameters (α, ω, κ, x_p, y_p, f, λ, μ, ν) in a least-squares adjustment. There are 13 unknowns in the new model which rigorously define the camera parameters.

MODELS FOR RADIAL AND DECENTERING DISTORTION

The distortion, δr, of a perfectly centered lens referred to the Gaussian focal length, f, can be expressed as

$$\delta r = K_1 r^3 + K_2 r^5 + K_3 r^7 + \ldots \qquad (2)$$

in which K_1, K_2, K_3 are coefficients of radial distortion and r is the radial distance referred to the principal point.
More specifically,

$$r = [(x - x_p)^2 + (y - y_p)^2]^{1/2}$$

where x, y are the plate coordinates of the photographed collimator points and x_p, y_p are the coordinates of the principal point. The x-y components of radial distortion are given by

$$\begin{aligned} \delta x = \delta r \left(\frac{x}{r}\right) &= x(K_1 r^2 + K_2 r^4 + K_3 r^6 + \ldots) \text{ and} \\ \delta y = \delta r \left(\frac{y}{r}\right) &= y(K_1 r^2 + K_1 r^4 + K_3 r^6 + \ldots). \end{aligned} \qquad (3)$$

The number of coefficients required to represent radial distortion with sufficient accuracy depends on the particular lens. Mapping lenses generally require two or three coefficients. Unusual lenses such as fisheye lenses may require several more, whereas a simple lens may require only a single coefficient.

After computing the appropriate coefficients, it is customary for practical production usage to transform the Gaussian distortion function (Equation 2) to a form in which the maximum positive and negative values of the distortion are equal. It was shown by Brown (1957) that a change, Δf, in the computed focal length results in a more useful distortion function given by

$$\begin{aligned} \delta r &= \frac{\Delta f}{f} + (K_1 + \frac{\Delta f}{f})r^3 + (K_2 + \frac{\Delta f}{f})r^5 + (K_3 + \frac{\Delta f}{f})r^7 + \ldots \\ &= K'_0 + K'_1 r^3 + K'_2 r^5 + K'_3 r^7 + \ldots \end{aligned}$$

The K' values will be reported in the calibration report along with the associated focal length, f.

DECENTERING DISTORTION MODEL

Slight misalignments in lens assembly introduce what is termed decentering distortion. This distortion has both a radial and tangential component and can be described analytically by the expressions that follow (Brown, 1966):

$$\begin{aligned} \Delta x &= \left[1 + P_3^2 r^2\right] \left[P_1 (r^2 + 2x^2) + 2P_2 xy\right] \\ \Delta y &= \left[1 + P_3^2 r^2\right] \left[2P_1 xy + P_2 (r^2 + 2y^2)\right] \end{aligned} \qquad (4)$$

where P_1, P_2, P_3 are unknown coefficients of decentering lens distortion. The higher order coefficient, P_3, only rarely proves to be significantly different from zero in today's aerial cameras.

The P_1, P_2, P_3 quantities in Equation 4 are actually parameterized terms of the actual decentering parameters Φ_0, J_1, J_2. These are introduced to simplify the computations (Livingston, 1980).

$$\begin{aligned} P_1 &= J_1 \sin \Phi_0 \\ P_2 &= J_1 \cos \Phi_0 \\ P_3 &= J_2/J_1 \end{aligned}$$

Reversal of these relations yields

$$\begin{aligned} \Phi_0 &= \text{arc tan } (P_1/P_2) \\ J_1 &= (P_1^2 + P_2^2)^{1/2} \\ J_2 &= (J_1)(P_3) \end{aligned}$$

where

Φ_0 = angle between the positive x axis and the axis of maximum tangential distortion, and

J_1, J_2 = coefficients of decentering distortion to be reported in the calibration report from the new system.

THE TOTAL SMAC MODEL

The model is composed of three parts: (1) projective equations of photogrammetry, Equation 1; (2) the radial distortion model, Equation 3; and (3) the decentering distortion model, Equation 4. Equation 5 represents the totally rigorous SMAC model. Table 2 shows a comparison of the current program output with the SMAC. Notice that the Ks and J_1, J_2, and Φ_0 are the additional values obtained by SMAC. Table 3 is a comparison of the calibrated values from an actual camera known to have large decentering distortion. Notice the 15 µm at 40° is reflected in the SMAC output. The current system offsets the x_p, y_p considerably as a result of the decentered lens, but it cannot directly account for the decentering as distortion. For the high quality cameras manufactured today, decentering distortion is generally expected to be near zero, but it will be defined. This may be a measure of the camera quality as well of precision in assembly of the lenses. However, in some state-of-the-art lenses decentering distortion may actually be significantly greater in magnitude than radial distortion. This may be largely due to computer lens designs where the designer may suppress radial distortion to a very low level, but the alignment and fabrication of the lens elements remains a tedious manufacturing step as in the past.

TABLE 2. COMPARISON OF PROGRAM OUTPUTS: CURRENT VS NEW SMAC

Current Program	New SMAC Program	Definition
• x_p, y_p	x_p, y_p	Coordinates of Principal Point
• f	f	Calibrated focal length
• α, ω, κ	α, ω, κ	Orientation angles
• ▬	K'_0, K'_1, K'_2, K'_3	Coefficients of radial Distortion
• ▬	J_1, J_2, Φ_0	Parameters of Decentering Distortion
• Radial Dist. Table	Radial Dist. Table	Radial Distortion - Each Diagonal
• ▬	Decentering Distortion Table	Decentering Distortion - Each Diagonal

• All other parameters Resolution, Fiducial Coordinates, Shutter Efficiency, Stereomodel Flatness, etc., will remain as currently reported.

TABLE 3. CURRENT SYSTEM VS SMAC FOR A REAL CAMERA

• Angle	Current System Average Distortion	SMAC Radial Distortion	SMAC Decentering Distortion
7.50°	−8 μm	−5 μm	0 μm
15.00°	−8	−7	1
22.75°	−3	−4	2
30.00°	4	3	4
35.00°	3	7	6
40.00°	0	1	9
• Parameters			
x_p	21 μm	5 μm	–
y_p	−47	−21	–
f	152.599 mm	152.597 mm	–
K'_0	–	0.254×10^{-3}	–
K'_1	–	-0.553×10^{-7}	–
K'_2	–	0.241×10^{-11}	–
Φ_0	–	–	213°
J_1	–	–	0.558×10^{-6}

$K_3 = J_2 = 0$ (insignificantly different from zero by statistical test)

Simultaneous Multiframe Analytical Calibration - SMAC

• Calibration Math Model

$$x - x_p = f\left[\frac{A\lambda + B\mu + C\nu}{D\lambda + E\mu + F\nu}\right] + x\left[K_1r^2 + K_2r^4 + K_3r^6\right]$$

Projective Equation Radial Distortion

$$+\left[1 + P_3^2r^2\right]\left[P_1(r^2+2x^2) + 2P_2xy\right] \quad (5)$$

Decentering distortion

$$y - y_p = f\left[\frac{A'\lambda + B'\mu + C'\nu}{D\lambda + E\mu + F\nu}\right] + y\left[K_1r^2 + K_2r^4 + K_3r^6\right]$$

$$+\left[1 + P_3^2r^2\right]\left[2P_1xy + P_2(r^2+2y^2)\right]$$

CONCLUDING REMARKS

In the past, many of the metric shortcomings of mapping cameras could be tolerated by virtue of the compensation provided by fairly dense networks of pre-established ground control. Establishing dense networks of control constitutes a major expense for mapping operations in both time and money. Mainly for this reason, coupled with advances in computer technology and photogrammetric instrumentation, the extension and densification of mapping control by means of block analytical aerotriangulation has gained widespread acceptance. Experiments by Brown (1966) have shown that the full promise of analytical methods depends in great measure on the precise calibration of the camera. This is because residual systematic errors propagate through analytical aerotriangulation in a most unfavorable manner.

It follows that the more comprehensive and more precise the calibration of the camera, the lower the requirements for absolute control in photogrammetric operations. The introduction of the more rigorous SMAC system at the USGS may be of fundamental importance to geodetic photogrammetry, to analytical photogrammetry, and to photogrammetric instrumentation nationwide.

The intent of this paper is to show the general equation form of the new calibration system and thereby to assist the users of the calibration report to better understand its value. The development team for the project is composed of Brad Johnson, George Schirmacher, Edward Cyran, and Donald L. Light of the USGS. Conversion of the original SMAC Code to the USGS system is being handled by Michael Babba and Thomas Riding of DBA Systems. Finally, testing and implementation of the system at the USGS is planned for completion by the end of 1991.

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REFERENCES

Bean, R. K., 1962. U. S. Geological Survey Camera Calibrator. Presented at the ACSM-ASP Annual Convention, Washington, D.C.

Brown, D. C., 1956. *The Simultaneous Determination of the Orientation and Lens Distortion of a Photogrammetric Camera,* AF Missile Test Center Technical Report No. 56–20, Patrick AFB, Florida.

———, 1957. *A Treatment of Analytical Photogrammetry with Emphasis on Ballistic Camera Applications,* AF Missile Test Center Technical Report No. 57–22, Patrick AFB, Florida.

———, 1966. Decentering Distortion and the Definitive Calibration of Metric Cameras, *Photogrammetric Engineering,* 42(5):xxx–xxx.

———, 1968. *Advanced Methods for the Calibration of Metric Cameras.* U.S. Army Engineer Topographic Laboratories Final Report under Contract DA-44-009-AMC-1457 (X), Fort Belvoir, Virginia.

Case, James B., 1955. Stellar Methods of Camera Calibration, Chapter 4 in *Manual of Photogrammetry,* 3rd Edition, American Society of Photogrammetry, Falls Church, Virginia, pp. 187–189.

Conrady, A., 1919. Decentered Lens Systems, *Monthly Notices of the Royal Astronomical Society,* 79:384–390.

Gyer, M. S., N. N. Haag, and S. K. Llewellyn, 1970. *Documentation for the Multi-Camera Stellar SMAC Computer Program.* U.S. Army Engineer Topographic Laboratories final report, DBA Systems.

Karen, R. J., 1968. Camera Calibration by the Multicollimator Method. *Photogrammetric Engineering,* 34(7):706–719.

Livingston, R. G. (ed.), 1980. Aerial Cameras, Chapter 4 in *Manual of Photogrammetry,* Fourth Edition (C. C Slama, editor). American Society of Photogrammetry, Falls Church, Virginia, pp. 261–263.

Schmid, H., 1953. *An Analytical Treatment of the Orientation of a Photogrammetric Camera,* Ballistic Research Laboratories Report No. 880. Aberdeen Proving Ground, Maryland.

Tayman, William P., 1974. Calibration of Lenses and Cameras at the USGS. *Photogrammetric Engineering,* 40(11):1331–1334.

———, 1978. Analytical Multicollimator Camera Calibration, *Photogrammetria,* 34:179–197.

———, 1984. Users Guide for the USGS Aerial Camera Report of Calibration. *Photogrammetric Engineering & Remote Sensing,* 50(5):577–584.

Tayman, W. P., and Hartmut Zieman, 1984. Photogrammetric Camera Calibration, *Photogrammetria,* 39:31–53.

Tayman, W. P., R. Vraga, and E. G. Schirmacher, 1985. *USGS Procedures Manual: Calibration of Aerial Mapping Cameras.* U. S. Geological Survey, Reston, Virginia.