User Guide for the USGS Aerial Camera Report of Calibration*

The various sections of the Report are discussed with reference to the current USGS aerial photography procurement specifications.

INTRODUCTION

The basic philosophy behind the calibration methods used by the U.S. Geological Survey (USGS) is to obtain camera calibration constants that will be applicable to a camera's normal use. The USGS photographic method of camera calibration approximates these as closely as possible. In order to avoid the random errors encountered in aerial use or in field calibration, the USGS calibrations are laboratory conducted. As far as is practical, the USGS calibration methods are in accordance with the International Society for Photogrammetry and Remote Sensing's Recommended Procedures for Calibrating Photogrammetric Cameras and for Related Equipment.

ABSTRACT: Calibration and testing of aerial mapping cameras includes the measurement of optical constants and the check for proper functioning of a number of complicated mechanical and electrical parts. For this purpose the U.S. Geological Survey performs an operational type photogrammetric calibration. This paper is not strictly a scientific paper but rather a "user guide" to the USGS Report of Calibration of an aerial mapping camera for compliance with both Federal and State mapping specifications. The various sections of the Report are discussed with reference to the current USGS aerial photography procurement specifications.

Optical Tests, adopted at the Society Congress in 1960. Since adoption, these standard procedures have been modified or reaffirmed by each succeeding Congress, held every four years. Due to the extreme environmental conditions of temperature and pressure changes, vibration, or shock to which an aerial camera is subjected, the precise alignment and spacing of the eight or more optical elements of a modern lens system can change and affect the lens performance. For this reason, the USGS requires a camera to have been calibrated within a three-year period prior to the scheduled opening date of a procurement solicitation. For reference, a sample Report of Calibration on a typical aerial mapping camera is included as a part of this paper (Figure 1). Following the Report is a reprint of a section from a USGS Invitation For Bids solicitation for aerial photography (Section C, Part 7, Camera). Except for high altitude photography, the USGS no longer issues standard specifications for aerial photography in a separate booklet. The applicable focal length specifications are included in the solicitation. Section C lists the items to be included in a Report of Calibration and measurement requirements. The Report of Calibration


Table 1. Sample Report of Calibration of Aerial Mapping Camera

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Camera Type</td>
<td>1205</td>
</tr>
<tr>
<td>Lens Speed</td>
<td>1:40</td>
</tr>
<tr>
<td>Standard Field Length</td>
<td>100</td>
</tr>
<tr>
<td>Reference Lines</td>
<td>100</td>
</tr>
</tbody>
</table>

Field of view: 5° x 5°, 20° x 20°, 30° x 30°, 40° x 40°

The optical distortion is measured for each roll of film and for each frame within a roll. The distortion is determined by comparing the measured field length with the calculated principal point of the camera. The distortion is then corrected using a mathematical model that takes into account the lens distortion and the normal orientation of the camera. The corrected field length is then used to calculate the actual orientation angles of the camera. The orientation angles are then used to determine the position and orientation of the camera at each frame within a roll. This information is then used to create a map of the area being photographed.
7. Cameras
a. Calibrated precision aerial cameras that can take aerial photographs compatible with the precision stereoscopic mapping instruments used by the Geological Survey are required. In order to verify that each camera meets this requirement, a complete calibration of the camera system shall be performed to determine the following:
(1) Calibrated focal length.
(2) Radial distortion.
(3) Resolving power from center to edge of field.
(a) Filter parallelism.
(b) Filter anti-vignetting gradient density coating trace (for cameras calibrated since February 1980).
(5) Shutter speed and efficiency.
(6) Film—slates flatness and identification.
(7) Location of the corner and include fiducials and point of symmetry with reference to the principal point of autocollimation.
(b) x, y fiducial coordinates.
(8) Distances between fiducial marks and 90° condition angle measurements.
(9) Stereomodel flatness measurements for cameras of 133-mm and 98-mm (6-inch and 3.5-inch) focal length.

b. The above measurements must have been performed within a three (3) year period prior to the scheduled opening date of the solicitation and the camera must meet the following requirements. (1) For 7a.1 through 7a.3. The characteristics of a nominal 6-inch camera shall be as follows:
(a) Focal length, 133 ± 3.0 mm, Universal Aviron, Pleonog A, or equivalent.
(b) Usable angular field, at least 90°.
(c) The following table lists the minimum acceptable radial and tangential resolution in cycles (line pairs) per millimetre (measured with type V-F spectroscopic emulsion on micro-flat glass plates exposed at maximum lens aperture):

<table>
<thead>
<tr>
<th>Cycle</th>
<th>0°</th>
<th>5°</th>
<th>10°</th>
<th>15°</th>
<th>20°</th>
<th>25°</th>
<th>30°</th>
<th>35°</th>
<th>40°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plates</td>
<td>57</td>
<td>57</td>
<td>48</td>
<td>49</td>
<td>34</td>
<td>34</td>
<td>14</td>
<td>14</td>
<td>14</td>
</tr>
</tbody>
</table>
(3) For 7a.1 through 7a.3. The characteristics of a nominal 3½-inch focal length camera shall be as follows:
(a) Focal length, 88 ± 4.0 mm, Super Aviron II, S-Pleogon A, or equivalent.
(b) Usable angular field, at least 120°.
(c) The following table lists the minimum acceptable radial and tangential resolution in cycles (line pairs) per millimetre (measured with type V-F spectroscopic emulsion on micro-flat glass plates exposed at maximum lens aperture):

<table>
<thead>
<tr>
<th>Cycle</th>
<th>0°</th>
<th>5°</th>
<th>10°</th>
<th>15°</th>
<th>20°</th>
<th>25°</th>
<th>30°</th>
<th>35°</th>
<th>40°</th>
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</thead>
<tbody>
<tr>
<td>Plates</td>
<td>59</td>
<td>59</td>
<td>49</td>
<td>42</td>
<td>35</td>
<td>30</td>
<td>17</td>
<td>14</td>
<td>12</td>
</tr>
</tbody>
</table>
(4) For 7a.1 through 7a.3. The characteristics of a nominal 8½-inch focal length camera shall be as follows:
(a) Focal length, 210 ± 4.0 mm, Normal Aviron II, Topanog A, or equivalent.
(b) Usable angular field, at least 70°.
(c) The following table lists the minimum acceptable radial and tangential resolution in cycles (line pairs) per millimetre (measured with type V-F spectroscopic emulsion on micro-flat glass plates exposed at maximum lens aperture):

<table>
<thead>
<tr>
<th>Cycle</th>
<th>0°</th>
<th>5°</th>
<th>10°</th>
<th>15°</th>
<th>20°</th>
<th>25°</th>
<th>30°</th>
<th>35°</th>
<th>40°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plates</td>
<td>49</td>
<td>49</td>
<td>42</td>
<td>35</td>
<td>29</td>
<td>29</td>
<td>29</td>
<td>29</td>
<td>29</td>
</tr>
</tbody>
</table>
(4) For 7a.1 through 7a.3. The characteristics of a nominal 13-inch focal length camera shall be as follows:
(a) Focal length, 302 ± 5.0 mm, Aviator I and II, Topanog A, or equivalent.
(b) Usable angular field, at least 50°.
(c) The following table lists the minimum acceptable radial and tangential resolution in cycles (line pairs) per millimetre (measured with type V-F spectroscopic emulsion on micro-flat glass plates exposed at maximum lens aperture):

<table>
<thead>
<tr>
<th>Cycle</th>
<th>0°</th>
<th>5°</th>
<th>10°</th>
<th>15°</th>
<th>20°</th>
<th>25°</th>
<th>30°</th>
<th>35°</th>
<th>40°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plates</td>
<td>48</td>
<td>48</td>
<td>28</td>
<td>28</td>
<td>24</td>
<td>24</td>
<td>24</td>
<td>24</td>
<td>24</td>
</tr>
</tbody>
</table>
(d) Radial distortion in the stable angular field based on the calibrated focal length referred to the calibrated principal point (point of symmetry) shall not exceed 0.020 mm.

(5) For 7a (d).

(d) An appropriate glass filter with a metallic antiglare coating shall be used. A microdensitometer trace shall be made and recorded of the antiglare coating located on the lens side of the filter. A copy of this trace shall accompany the report of calibration to determine if any deterioration has occurred to the coating that would affect the uniformity of illumination in the image plane. The filter shall have surfaces parallel within 10 seconds of arc, and its optical quality shall be such that its addition to the camera shall not enter an undesirable reduction of image definition. A minus-blue glass filter shall be used with panchromatic emulsions.

(6) For 7a (d).

(a) The camera shall be equipped with a between-the-lens shutter of variable speed as approved by the Contracting Officer. The range of speed settings shall be such that, in conjunction with flight height and aircraft speed, the camera will produce high definition photographs. The shutter shall also have a speed of 1.200 second or slower for laboratory testing.

(b) The effective exposure time and the efficiency of the shutter as mounted in the camera will be measured at maximum aperture, and the shutter shall have a minimum efficiency of 76 percent at a speed of 1.200 second.

(c) This test shall be made in accordance with "Method 1, American National Standard PH23-45-1972 (R1978).

(7) For 7a (d).

(d) Cameras shall be equipped with an apparatus (e.g., of flattening the film at the instant of exposure. The plate against which the film is pressed shall not depart from a true plane by more than ± 0.013 mm (0.0005 inch) when the camera magnesium vacuum is applied. The iron number, an alphanumeric mark or symbol) which identifies the plate used and the most recent calibrated focal length shall be recorded clearly on the film for each negative either on the inside of the focal plane frame or on a data strip between frames. Data markers which protrude inside the focal plane frame shall not exceed 0.35 mm (0.025 inch) in height and 25.4 mm (1.0 inch) in length and shall not obscure any part of the fiducial mark or reduce the usable image area.

(8) For 7a (7) through 7a (8).

(a) Each camera body shall be equipped with means of recording eight fiducial marks on each exposure, the marks to be located in each corner of the format and at the center of each side (see Exhibit B). The corner fiducial marks shall form a quadrilateral whose sides are equal within 0.300 mm. The midside fiducial marks shall be equidistant within 0.500 mm from the adjacent corner fiducial marks. Lines joining opposite pairs of fiducial marks shall intersect at an angle of 90° ± 1 minute and indicate the position of the principal point of autocollimation within 0.020 mm. The fiducial centers and the point of symmetry shall fall within a 0.003 mm radius circle around the principal point of autocollimation. For cameras with projection type fiducial marks, the projected images of all marks must be in focus on the emulsion surface. Any camera containing glass or plastic amounts of the fiducial marks will not be acceptable.

(b) All fiducial marks and other markings intended for precise measuring shall be clear and well defined on the negative and shall be of such a form that the standard deviation of repeated readings of the coordinates of each mark on a comparator shall not exceed 0.002 mm. Drawings in Exhibit 2 show examples of fiducial marks.

(c) The size of the negative image shall be 23 x 23 cm (9 x 9 inches).

(9) For 7a (d).

Cameras will be tested for stereomodel flatness by exposing two films negatives in the camera which is mounted on the multi-camera camera calibration and analytically forming two stereo models from them, using different halves of the exposures for each model. Each model thus formed will consist of a small fixed number of symmetrically arranged points. In either model, the deviation of flatness (deflection discrepancy) at photography scale at measured points may not exceed ± 1/5000 of the focal length of nominal 6-inch (152 x 3.0 mm) cameras. The deviation max not exceed ± 1/5000 of the focal length of nominal 3½-inch (88 x 4.0 mm) cameras. If ele-
viation discrepancies exceed this value, the camera will not be acceptable.

c. Bidders are required to either have on file with the U.S. Geological Survey, National Mapping Division, Branch of Contract Management an acceptable report of calibration or submit such report with their bids. The advance of a Report of Calibration will be cause for the rejection of bids. The bidder's failure to provide the required Report of Calibration due to delays encountered by the testing facility shall not be considered reason for the Government to accept bids lacking such reports.

d. Prospective bidders and contractors requesting camera calibration shall ship their camera(s), including magazine(s), filters, controls, and complete operating instructions, to Mr. William Tayman, U.S. Geological Survey, National Center (Stop 526), Reston, VA 22092. A schedule for the test must be made by contacting Mr. Tayman (703-960-6252). The combination of camera cone and magazine(s) submitted for testing, if acceptable, shall be the only combination used to take seretical photographs on U.S. Geological Survey contracts. Any other combination of cone and magazine(s) shall be considered an untested camera system and shall be reason for rejection of bids or rejection of any resulting photography.

e. The USGS reserves the right to test a camera at anytime there is reason to believe that changes have occurred that would prevent the use of any resulting photographs. In the event retesting of a camera is required by the U.S. Geological Survey, the bidder shall submit the camera, including magazine(s), filters, and controls, to the USGS for laboratory retest within five (5) days after receipt of USGS notice for retesting. Notice issued by the U.S. Geological Survey that a camera requires retesting shall render previous reports of calibration invalid for future photography requirements of the USGS.

f. Laboratory tests (including retesting as described herein above) take approximately seven (7) days. The contractor shall bear the expense of testing and shipment to and from the USGS. Unless specified otherwise by the prospective bidders, cameras returned to the original shipper will be insured at the original shipper's expense for the same value as when received.

1. CALIBRATED FOCAL LENGTH

The focal length normally reported in a lens test is the equivalent focal length (EFL). However, in photogrammetry a calibrated focal length (CFL) is determined to minimize the plotting error due to distortion. The CFL is the scale factor used to convert transverse distances in the image plane of a photograph into corresponding distances in the object plane or in the scene photographed. For the image plane, it is determined by the radial distance of the image divided by the tangent of the half-field angle.

If the value varies across the image plane, it is an evidence of distortion which is normally expressed as the differential in radial distance required to keep the focal length constant. The CFL reported is the value that makes the positive and negative values of distortion equal when computed by the method of least squares. The CFL is the limiting value as the field angle goes to zero. If there is no distortion, the CFL and EFL are identical. The difference between the equivalent focal length and the calibrated focal length can be expressed as the value of $\Delta f$ determined from the relation

$$\Delta f = (D_1 - D_2)/\tan B_1 + \tan B_2$$

where $D_1$ and $D_2$ are the values of distortion, referred to the equivalent focal length, at angles $B_1$ and $B_2$ for which equal but opposite values of distortion are desired. It should be emphasized that no physical shift of the focal plane takes place between the CFL and EFL. The only change is in the choice of a scale factor for use in interpreting measurements of distance separating various image points.

2. RADIAL DISTORTION

Distortion affects positions of image points in the image plane but not image reality. Distortion is a variation of scale of an image as a function of position in the image plane. The presence of distortion of great importance in photogrammetry where the ultimate aim is to produce maps of uniform scale from measured images. The standard USGS procedure is to measure the radial distortion from a camera's format center to the corner along each diagonal. To minimize the maximum distortion displacement of the principal rays over the field, a least-squares solution is used to equalize the positive and negative values of distortion. The distortion is reported in micrometers at the collimator angle positions of the calibrator. Modern lenses today are nearly free of radial distortion, with measured values being under 10 micrometers based on the calibrated focal length referred to the calibrated principal point (point of best symmetry).

3. RESOLVING POWER

Resolving power is a numerical measure of lens performance, related to image definition. However,
one should always consider the fact that resolution is a much a function of the receptor and the emulsion as of the optical system. Resolution of a particular lens and film together can never be more than that of the lens or the film, whichever is the lower. It is for this reason that the tricks measured resolving power on both fine-grain and medium-grain emulsions such as Kodak 400 and 2400.

In Section III of the Report of Calibration, the resolving power obtained with the fine-grain or high-definition emulsion is given. The values given in Section X are for the fast panchromatic film emulsion used for standard CCIK-type photographic experiments. Regardless of the grain size, both test emulsions have the same spectral sensitivity. The light source used in the test collimators is approximately 5,200K, considered to be noon sunlight. The test collimators have high-contrast resolution test charts as reticles. These charts have 24 three-line test patterns spaced at the fourth root of 2. For a 153-mm (6-inch) lens, the test patterns are 5 cycles (line pairs) per millimetre (chart 1) to 28 cycles per millimetre (chart 24).

The contract specifications list the minimum acceptable radial and tangential resolution in cycles per millimetre for the various field angles. These test values are given in Section III of the report. Also stated in the specifications are the type of test emulsion and the requirements that resolution test exposure be made at maximum lens aperture.

IV. FILTERS

The filters are measured to determine if the prismatic power is less than 10 seconds of arc, as required in the camera specifications. If the lack of parallaxis is greater than 10 seconds of arc, the position of the principle point of autocollimation will shift, introducing unacceptable asymmetrical distortion. The density of the antivignetting coating of a filter is designed to correct the light distribution of the photographic lens with which it is used. A unique density gradient envelope is therefore specified. For each filter, this gradient is measured and compared with the specified envelope, while the coating is visually inspected for deterioration which would affect the uniformity of illumination at the camera lens system.

Each filter that meets the specifications requirements for parallaxis is listed in Section IV of the Report of Calibration. Accompanying the report are microdensitometer curves showing the filter's measured antivignetted coating and a superimposed dashed line showing a normal curve when the measured coating curve is cut out of tolerance.

V. DUTY CALIBRATION

The USGS camera specifications specify the type of shutter, range of speed, minimum efficiency, and method of test. As stated in the specifications, the technique used in the camera calibration is Method I described in American National Standard PS 3-48-1972 (R 1975).

Normally, values are reported at the following indicated settings at maximum aperture, giving measurements for the effective shutter speed and efficiency.

- 1/200 second
- 1/400 second
- 1/600 second
- 1/900 second
- 1/1000 second

VI. MAGAZINE PLATE

The plates are the flat surface against which the back surface of the film is pressed to ensure plane-ness of the emulsion surface during the time of exposure. Its outer edges overlap the camera focal plane frame. It is essential that the plate surface be a true plane because small departures from plane-ness in this surface can produce shifts in image location similar to those produced by lens distortion. The specifications state the plate against which the film is pressed shall not depart from a true plane by more than 0.013 mm (0.0005 inch) when the camera/magazine vacuum is applied. Also included in this section of the report is the plate identification statement. The specifications require an alphanumeric mark (or symbol) which identifies the magazine plate. This mark or symbol will register on each exposure in the data strip area of the camera format.

VII. PRINCIPAL POINT AND OPTICAL COORDINATES

The x/y coordinates given in this section of the report are referenced to the principal point of autocollimation (PP) as origin. If lines are drawn across the camera format connecting opposite fiducials 1-2, 3-4, and A-B, C-D, the intersections of these lines are the indicated principal points for either the corner or midline fiducials. The principal point of autocollimation (PP) is the location at which the C collimator is recorded on the test negative when the focal plane is perpendicular to the axis of this collimator. The calibrated principal point (point of best symmetry) is the shift that is necessary from the PP to reduce the asymmetry of the distortion to a minimum. If there were no asymmetric distortion, this value would be zero. For specification compliance, the indicated principal point shall be within 0.039 mm of the PP. The point of best symmetry shall be within a 0.039-mm radius circle around the PP.

The x/y coordinates reported for the fiducials 1 through 8 are measurements made on the rigid emulsion of 1.5-mm thick microfilm glass plates. The accuracy of these measurements depends on the quality of the imagery recorded. For clear, finely-lined, well-defined center dots, these measurements are accurate within a few micrometers. The
VIII. DISTANCES BETWEEN FIDUCIAL MARKS

The distances separating the members of opposite pairs of fiducial marks are constants that have specified requirements for length and angle intersect. The corner fiducial marks shall form a quadrilateral whose sides are equal within 0.500 mm. The mid-side fiducial marks shall be equidistant within 0.500 mm from the adjacent corner fiducial marks. Lines joining opposite pairs of fiducial marks shall intersect at an angle of 90° ± 1 minute of arc.

IX. STEREOMODEL FLATNESS

For specification compliance, the stereomodel distortion (Z-direction) shall not exceed 1/5000 of the flight height for cameras of 152-mm and 85- to 85-mm 6-inch and 3.5-inch focal length. With the camera functioning in the normal mode of operation, a number of film exposures are made to simulate aerial photographs. Fifteen of the target reflectors in the test instrument are so arranged that a pair of diapositives made from the exposed film form a stereomodel consisting of nine symmetrically arranged points (see Figure 2). That is, the right half of the diapositive serves as the left photograph of a stereopair and the left half of the diapositive serves as the right photograph of a stereopair. The left plate is held fixed and the right plate is oriented to it. The three-dimensional coordinates of the nine image points in the resulting stereomodel are computed by a least-squares solution. A regression plane for the best overall fit is made to the nine points, and the residual "lack of flatness" is determined.

For a camera to be acceptable, the deviation from flatness (elevation discrepancy at photograph scale) at the nine test points cannot exceed the following values. The values given in the report are the average departures from flatness for two stereomodels as shown in Figure 2.

<table>
<thead>
<tr>
<th>Camera Focal Length</th>
<th>Stereomodel Flatness</th>
</tr>
</thead>
<tbody>
<tr>
<td>53-58 millimetres</td>
<td>17 micrometres</td>
</tr>
<tr>
<td>152 millimetres</td>
<td>30 micrometres</td>
</tr>
</tbody>
</table>

The base-height ratio is 9:6 for cameras having a 50° field and 9:6 for cameras having a 120° field. Small defects in the cameras, such as variation from planarity of the film plane, irregularity of the film flattening system (various), distortions, corning of the camera lens elements, and nonparallelism of the filter surfaces, all contribute to the results of the stereomodel flatness measurements.

SELECTED REFERENCES


