CURRENT METRIC AERIAL CAMERA CALIBRATION IN THE U.S.

For

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Abstract

In the field of photogrammetry, it is necessary to periodically determine if the metric aerial cameras being used are continuing to function at the level at which they were designed and will return acceptably accurate measurements. The appropriate method for this determination is the use of the multi collimator at the SUGS Optical Science Laboratory in Reston, Virginia, and the SMAC least squares data reduction methodology for camera parameter determination. When this system is used, the calibrated cameras will deliver accurate, stable and repeatable results.

Current Metric Aerial Camera Calibration in the U.S.

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This paper will address the issues of metric aerial camera calibration in general and follow through with the calibration issue as it affects the United States. The paper will begin with the definition of and the need for camera calibration. It will then discuss the general process of calibration and the outputs from the calibration process.

Definition

At its essence, calibration is the establishment of numerical values for the metrological features according to accepted standards. This means that calibration is the measurement of accuracy and can be assessed in the relationship between a change in input and a change in output. [1]

For most industries, the above definition is perfectly suitable. The calibration of measuring instruments is a simplistic function: the gauge either meets the standard and can be used, or it does not meet the standard and cannot be used. However, for metric aerial cameras, the calibration process in some cases is intended to return information to the user and may or may not make any assessment of the instrument's suitability. So for the purpose of this paper, there is not one single definition or aspect of calibration. The three definitions of calibration to be used here are:

1. a method for the determination of critical system parameters to be reported to the user,
2. the determination of a single element's acceptability to known standards, and
3. the determination of an entire system's acceptability to known standards.

Need for Calibration

Metric aerial cameras need to be calibrated for a variety of reasons. The first and foremost reason is to find out if the camera is continuing to function at the level at which it was designed. This part of the calibration process is inspection to determine if the camera either meets the design criteria and can be used or it does not meet the criteria and cannot be used. [2]

The other classic function of camera calibration is to provide the photogrammetrist with the necessary system parameters for the compensation of systematic departures from the ideal true projection. (The definition of these systematic departs will be discussed later in this paper.) These departures then also extend to the variability of the final product as it would be impossible to determine the variability of the final product without understanding the variability of the measurement system. [2]

When used in combination with historical records and basic statistical control, camera calibration results can be used to determine camera stability and/or deterioration. While most of the current calibration organizations require that the camera be in working order before calibration, the calibration results may enable the user to predict at what point in time the camera will require adjustment or repair. The prediction is done by assessing if historically the individual parameter's results are normally distributed around a single point. If the past results are not normally distributed, then regression analysis should be used to determine when the results would go beyond the allowable limit. [1]

Lastly, calibration provides traceability. An axiom of the definition of calibration is that "calibration is the authentication of the accuracy lineage of any measurement system." This means that the calibration process automatically provides a "traceable" link to a higher accuracy standard. [1] This traceable link does three things:

1) minimizes error propagation,
2) ensures that the findings are consistent/repeatable/comparable, and
3) provides the final customer with some third party evidence that the final product meets all the necessary requirements.

Calibration Method

In the United States and most of North America, there is one method by which photogrammetric aerial cameras are calibrated. This calibration process is the Multi-collimator method. The multi-collimator is a series of optical collimators (projectors), focused at infinity and projecting a center cross and image resolution targets. The collimators are oriented in an array such that they point toward a common camera station. The center collimator establishes the directional origin to which banks of additional collimators are related at angular radial increments of about 7 ½ degrees along four banks. The actual function and design of the multi-collimator will be discussed later in this paper. [2]

Only one operational multi-collimator exists in North America. It is located at the United States Geological Survey (USGS) National Mapping Division's Optical Science Laboratory located in Reston Virginia (see the attached map in the appendix for the proximity to Washington D.C.). The USGS has, over time, proven to be the logical choice for operating the nation's calibration system. The primary reason for the USGS to run the system is that the USGS is the only independent agency in the United States with a stable, precise, aerial, photogrammetric camera calibration facility. [2] The USGS also does not perform most of the aerial photography it uses but contracts the function to independent subcontractors. As such, the USGS can maintain an impartial view of the results of the calibration and has no vested interest in the outcomes of the calibrations. [5]

Multi-Collimator

As stated in the opening of this section, the multi-collimator is a series of optical projectors, focused at infinity and projecting a center cross and image resolution targets to a camera mounted at the common focal point of the projectors, as shown in Figure 1 below. [8]

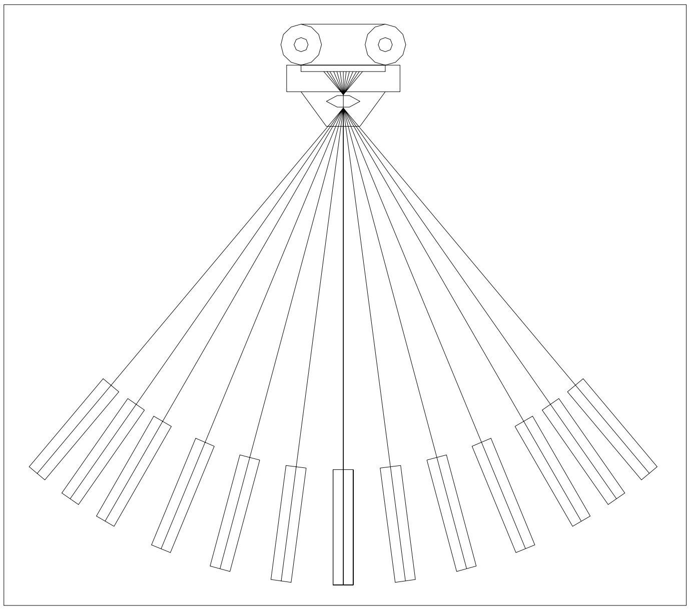


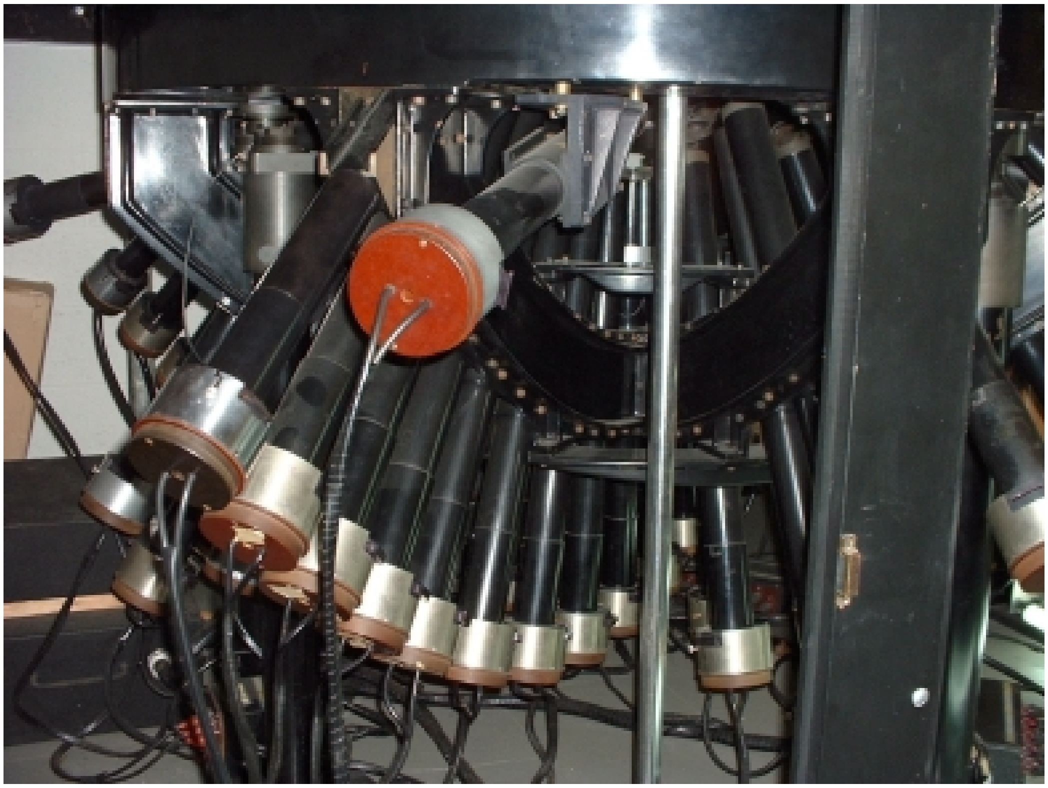
Figure 1

The intent of each of the collimators is to project its image using parallel light rays. The image then coincides with the infinite focus of the camera and thus can be captured correctly at the focal plane of the camera. The following is a picture of the projectors (Picture 1). [7]

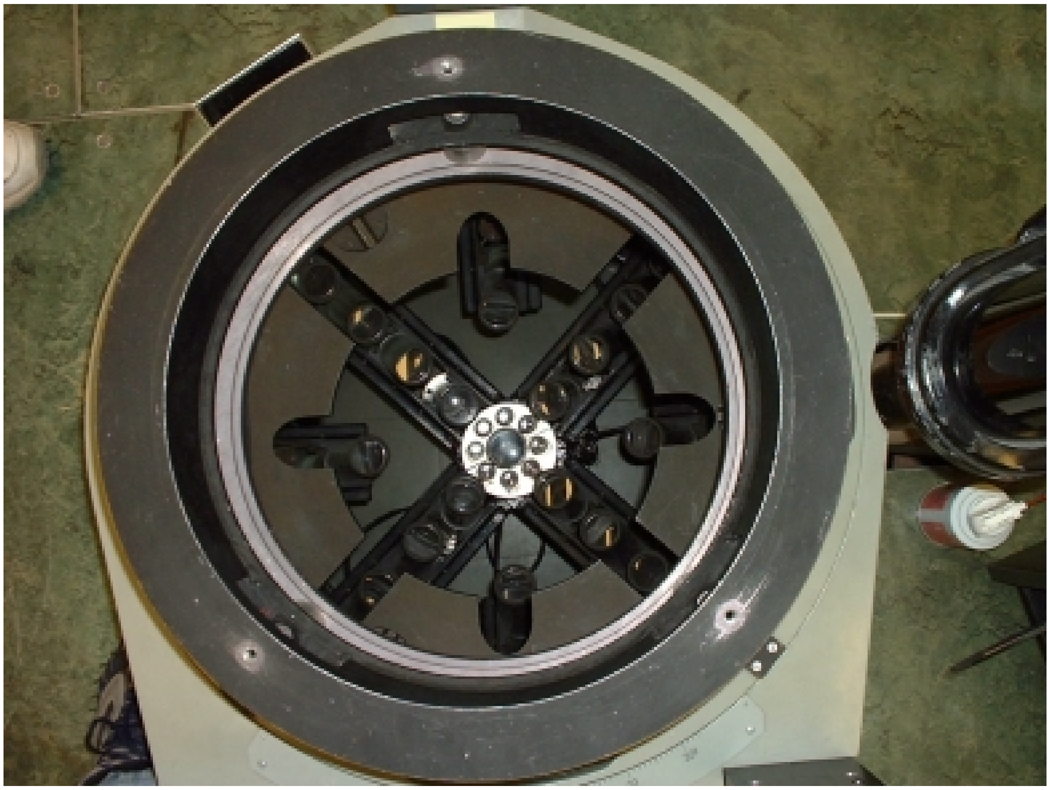
The multicollimator uses two sets of projectors in perpendicular planes. Using this configuration the multicollimator can project images across the entire camera image format. The camera is positioned so that the images from the collimators run across the diagonal of the media. Figure 1 shows one set (bank) of projectors. The other bank is oriented such that it would be coming out of the paper. The following Picture 2 is an image taken from above the bank of collimators, where the camera would be located. [7]

The projectors are permanently affixed in this array. The critical angle from vertical for each projector has been determined through an annual validation process using T-2 and T-3 theodolites. [7]

The projector's light source is a specially designed high output fluorescent bulb. The "firing" of the light source is controlled by a series of analog controllers. The light source and control system is out of date. According to the Optical Lab's manager, Frank Maccue, the multi-collimator will be updated with LED light sources and digital controls sometime before 12/2002. A picture of the current light bulb (Picture 3) and control panel (Picture 4) are shown below. [7]



Picture 1



Picture 2

Picture 3

Picture 4

Calibration Process

In the calibration process the camera is mounted above the collimators so the focal plane of the camera is perpendicular to the vertical collimator's axis. The camera is also positioned vertically so that the intersection of the projections is at the front nodal point of the camera's lens and rotationally so that the main projections from the collimators are aligned across the diagonals of the camera format. [7] The picture on the next page (Picture 5) shows the entire multicollimator and the camera mount (without a camera). Note: All model cameras have a unique mount, which is provided to the USGS by the manufacturer. [7]

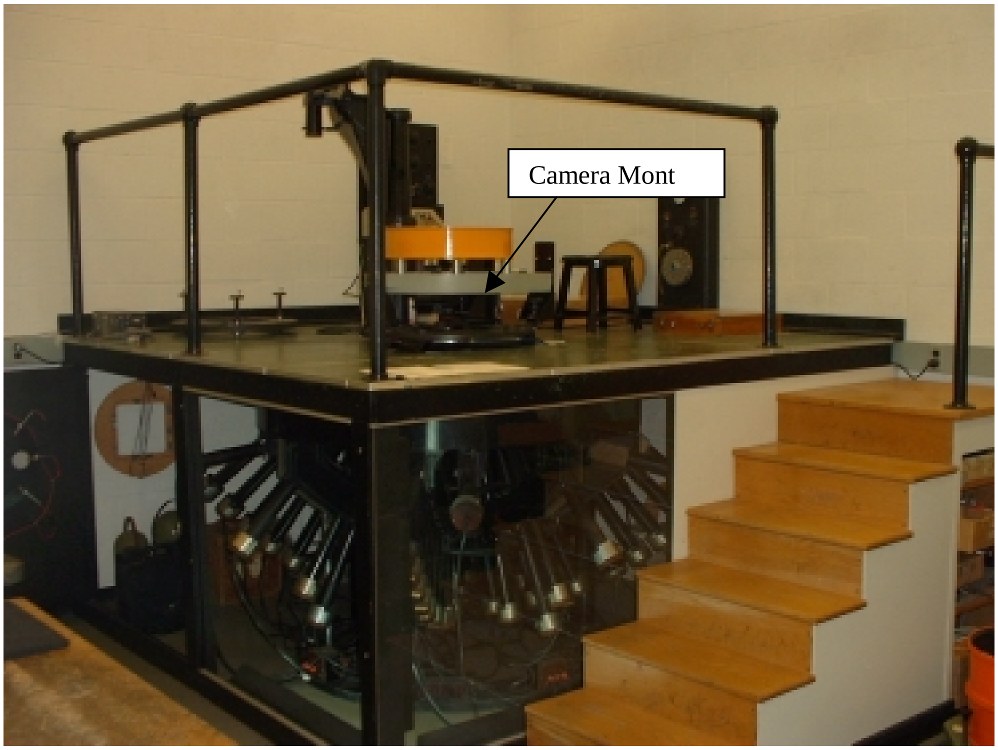
The second step is to place a photographic plate at the focal plane of the camera. The plate is an ultra flat (>.003mm) piece of glass and is positioned such that the emulsion remains in the camera's focal plane. Figure 2 on the next page shows the target positions as they appear on glass plates.

The camera is now ready for the exposures to be taken. Four exposures are taken for each camera, two from the original position and two after a 180° rotation. The positions of the camera and the glass plate are checked for movement after each exposure. [5]

The third step of the calibration process is to determine the acceptability of the focal-plan flatness. The flatness is a direct measurement of the platen that the film is pressed against during exposure. The measurement is done with standard metrology methods. A surface plate and surface gauge with a .00050" indicator are used in the measurement process. [7]
The last calibration operation performed on the camera is the shutter efficiency test. The test is intended to determine if the camera's shutter will open instantaneously, stay open for the specified exposure time, and close instantaneously. [5]

Elements of Calibration

Once the calibration process is finished, the elements of the calibration must be determined through measurements and a least-squares method estimation. (The measurements and least squares method will be addressed later in this paper.) The elements of calibration to be derived are as follows:



Picture 5

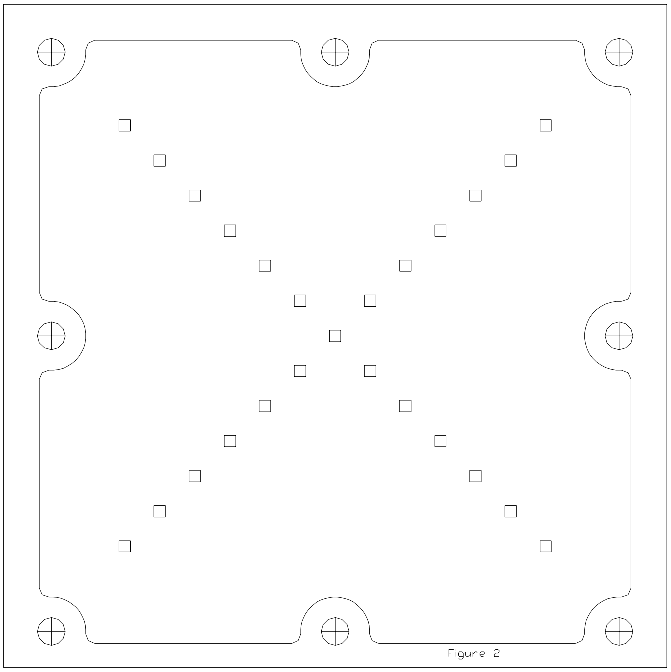


Figure 2

1. Calibrated Focal Length (CFL): The CFL represents the length from lens's rear nodal to the principle point of focus, located on the film platen. The CFL is also the distance that creates the mean distribution of the lens distortion. [8]

2. Principal Point of Autocollimation (PPA): The PPA as the origin location is the x and y coordinates of the vertical collimator's projection center (distorted by the lens) in terms of the fiducial marks. [8]

3. Symmetric Radial Lens Distortion: The symmetric distortion is the distortion that occurs along radial lines extending out from the principle point in all 360°. [8]

4. Decentering Lens Distortion: The decentering distortion is the distortion that occurs asymmetrically around the lens center and in some cases tangential to the lens system axis. [8]

5. Fiducial Mark Coordinates: The fiducial coordinates are the x and y coordinates of the camera's fiducial marks with reference to each other. [8]

6. Resolution: The resolution is a measurement to quantify the camera's resolving power. In other words, it is a measurement of the sharpness of the image produced. [8]

Measurement:

The main calibration of the camera comes from the measurement of the captured image from the collimator on the glass plates. Figure 3 shows a reproduction of the image projected by each collimator.

The projection shown in Figure 3 provides two types of measurable information. The first type is that of positional accuracy and the second type is resolving power. The positional accuracy is assessed by measuring the radial displacement of the x and y coordinates of the image's center "X" verses the location identified on the glass plate. This measurement is made by a comparator method. 7 The analog comparator used to take the measurements is shown below in Picture 6.

The measurement for resolution is performed manually. The measurement technician uses a low power magnification device at a set distance from the glass plate to determine what highest numbered set of "bars" can be counted with reasonable confidence. The measurements are converted to a scale of 5 to 268 cycles/mm in a geometric series. It is worth noting that the measurement is difficult and requires a good deal of experience before the technician's measurement can be considered repeatable. [7]

Calibration Parameter Calculations

The calibration parameters are determined by a rigorous least squares estimation known as the Simultaneous Multiframe Analytical Calibration (SMAC). The SMAC method is based on the original document Advanced Methods for the Calibration for the Calibration of Metric Cameras (Brown, 1968).

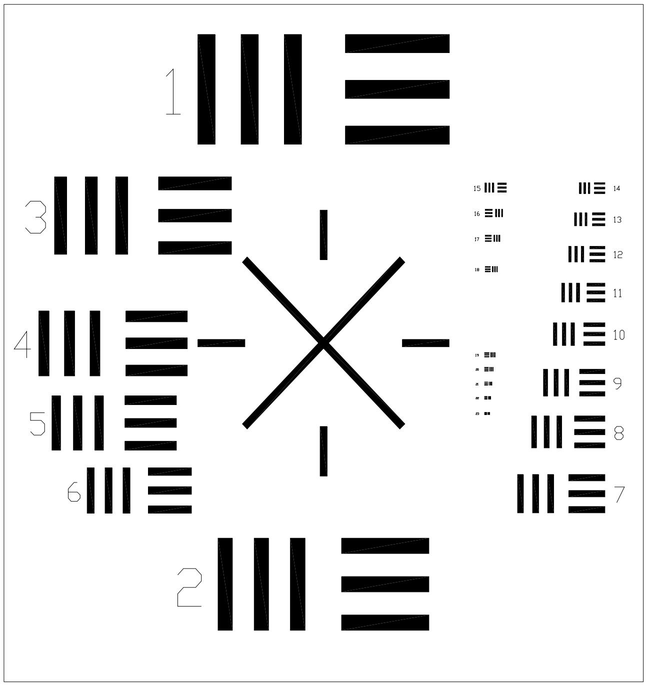


Figure 3

Picture 6

The SMAC method uses three components simultaneously to form the equations used in the reduction process. The components equations are: 1) the projective equations, 2) the radial distortion model, and 3) the decentering model. This combined equation accounts for all types of variation and provides the camera's user with the statistically minimized x and y offsets for each area of the image and all other key information. 4 The equations are as follows:

1) *Projective Equations*:

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

Where:

- x and y are the center glass plate coordinates.
- x_p and y_p are the coordinates of the determined principal point.
- f is the designed focal length of the camera
- A, B, C, A', B', C', D, E, F are orientation elements which are functions of the exterior orientation element κ, φ, and ω.
- λ, μ, ν are the directional cosines of lines connecting the object and the image.

2) *Radial Distortion Equations*:

$$\delta x = x\left(K_1 r^2 + K_2 r^4 + K_3 r^6\right) \qquad \delta y = y\left(K_1 r^2 + K_2 r^4 + K_3 r^6\right)$$

Where:

- the K's are coefficients of radial distortion
- r is the distance between x,y and x_p, y_p.

3) *Decentering Distortion Equations*:

$$\Delta x = \left[1 + \left(\frac{J_2}{J_1}\right)^2 r^2\right]\left[(J_1)\sin(\Phi_0)\left(r^2 + 2x^2\right) + 2(J_1)\cos(\Phi_0)xy\right]$$

$$\Delta y = \left[1 + \left(\frac{J_2}{J_1}\right)^2 r^2\right]\left[2(J_1)\sin(\Phi_0)xy + (J_1)\cos(\Phi_0)\left(r^2 + 2x^2\right)\right]$$

Where:

- Φ_o is the angle between the positive x axis and the axis of maximum tangential distortion.
- J_1 and J_2 are the coefficients of decentering distortion.

Therefore the model can be written as

$$x_c = f\left(\frac{A\lambda + B\mu + C\nu}{D\lambda + E\mu + F\nu}\right) + x\left(K_1 r^2 + K_2 r^4 + K_3 r^6\right) + \left[1 + \left(\frac{J_2}{J_1}\right)^2 r^2\right]\left[(J_1)\sin(\Phi_0)\left(r^2 + 2x^2\right) + 2(J_1)\cos(\Phi_0)xy\right]$$

$$y_c = f\left(\frac{A^1\lambda + B^1\mu + C^1\nu}{D\lambda + E\mu + F\nu}\right) + y\left(K_1 r^2 + K_2 r^4 + K_3 r^6\right) + \left[1 + \left(\frac{J_2}{J_1}\right)^2 r^2\right]\left[2(J_1)\sin(\Phi_0)xy + (J_1)\cos(\Phi_0)\left(r^2 + 2x^2\right)\right]$$

Where x_c and y_c represent the final corrected x and y coordinates for the individual points. [4]

Calibration Output:

The final output from the calibration process includes:

1) The Calibrated Focal Length as adjusted in the least squares process.
2) The Symmetric Radial Distortion in microns at each field angle.
3) The Decentering Distortion in microns at each field angle.
4) The Symmetric Radial Distortion parameters K_0, K_1, K_2, K_3, K_4.
5) The Decentering Distortion parameters P_1, P_2, P_3, P_4.
   Where $P_1 = J_1 \sin\Phi o$, $P_2 = J_1 \cos\Phi o$, and $P_3 = J_2 / J_1$
6) The Calibrated Principal Point in terms of the camera's reference frame.
7) The area-weighted average of the Lens Resolving Power in cycles per mm.

8) The individual readings of the Lens Resolving Power in cycles per mm along radial lines from the principal point at the collimator's field angles.
9) The individual readings of the Lens Resolving Power in cycles per mm along tangential lines at the collimator's field angles.
10) The Shutter Calibration information, including: rise and fall time, ½ width time, and nominal speed and percent efficiency, all at various shutter speed settings.
11) The Magazine Platen Flatness.
12) The x and y coordinates of the principal point and fiducial marks using the principal point of autocollimation as the point of origin.
13) The Distance Between Fiducial Marks, including the angle of intersection of opposing marks.
14) The nominal Entrance Pupil Distance, which represents the distance from the front nodal point to the focal plane.

All of these outputs are documented in a calibration report issued by the USGS. The reports are dated and serialized. A copy of the report is returned with the camera to the user and a paper copy is retained by the USGS. [7] (The USGS is currently in the process of scanning all past reports into a database.) A copy of an actual USGS calibration report is in the appendix.

Camera Calibration Specifications:

The USGS has determined basic calibration parameter specifications for various camera formats. The first specification is the calibration frequency. The USGS has determined that metric aerial cameras should be calibrated once every 36 months. [9] The following charts outline the remaining specifications:

Focal length	88 mm	153 mm	210 mm	305 mm
Focal length within	± 4 mm	± 3 mm	± 4 mm	± 5 mm
Usable angular field	120^{o}	90^{o}	70^{o}	50^{o}
Field angle-from axis out to:	54.5^{o}	40^{o}	30^{o}	22.7^{o}
DISTORTION - At maximum aperture				
Radial distortion - tolerance (µm)	± 15	± 10	± 20	± 20
Decentering distortion - tolerance (µm)	-	≤8	-	-
MODEL FLATNESS - (µm) total difference	± 17	± 19	-	-

Indicated principal points (Fiducial Centers)
The indicated principal points (fiducial centers), shall fall within a 0.030-mm radius circle around the principal point of autocollimation.

Calibrated Principal Point (Point of Symmetry)
The calibrated principal point - point of symmetry - shall fall within a 0.015-mm radius circle around the principal point of autocollimation for 153 mm focal length lenses and 0.030 mm for all others.

	Minimum Radial & Tangential Resolution in Line Pairs per Millimeter (Lp/mm) Half angle for each lens									
Focal Length	0^{o}	7.5^{o}	15^{o}	22.7^{o}	30^{o}	35^{o}	40^{o}	45^{o}	50^{o}	54.5^{o}
88 mm	59	59	49	42	35	30	17	14	12	12
153 mm	80	80	67	57	57	48	40	-	-	-
210 mm	49	49	42	35	29	-	-	-	-	-
305 mm	48	48	28	24	-	-	-	-	-	-

It is worthy to note that the calibration report issued by the USGS does not indicate if the camera has met these specifications. The report gives the numerical values for the parameters only and makes no judgment of the suitability of the camera. [7]

Conclusion:

It is necessary to periodically determine if the metric aerial cameras are continuing to function at the level at which they were designed and will return acceptably accurate data. This determination should be done at a minimum of once every 36 months. The appropriate method for this calibration is the use of the multi collimator at the USGS Optical Science Laboratory in Reston Virginia and the SMAC least squares data reduction methodology for camera parameter determination. When this system is used, the calibrated cameras will continue to deliver accurate, stable and repeatable results.

Acknowledgements

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