USGS/OSU PROGRESS WITH DIGITAL CAMERA *IN* SITU CALIBRATION METHODS

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ABSTRACT:

The United States Geological Survey (USGS) in cooperation with The Ohio State University (OSU) and Calgary University (CU) have developed procedures and software for the efficient calibration of metric quality aerial cameras; both film- and CCD-based sensors. With the advent of the Global Positioning System (GPS), and its efficient use to position the exposure station of the aerial camera, it became necessary to accurately establish camera interior orientation under operational circumstances (*in situ* calibration) to assure agreement of the photogrammetric procedure results with positional data provided by GPS. Disagreement between photogrammetric resection methods, based on laboratory calibration, and GPS results were consistently as large as one part in 1000 of the flight height. This paper describes the development of the airborne method of camera calibration, software development, and some results of accuracy improvements when using the *in situ* method of camera calibration.

1. INTRODUCTION

With the advent of the Global Positioning System (GPS) and other airborne sensors, it became necessary to revise the traditional concept of camera calibration. Influences on the camera and its spatial relationships to other sensors require that data used in calibration be collected under conditions closely approximating those expected in application of the photogrammetric system and its associated sensors (the *in situ* method).

This paper presents a revised concept of calibration of aerial photogrammetric systems. Justification for this revised approach to calibration is presented by comparing photogrammetric results to corresponding GPS results. These results, in terms of positional information, should be in agreement if the full spatial accuracy of GPS is to be exploited.

The US Geological Survey (USGS) sponsored development of appropriate software programs for use with the aerial method of calibration. Two programs are described for image measurement and calibration purposes. These programs are specialized to work in connection with use of aerial imagery, controlled by GPS, and taken over a suitably targeted control range. Either conventional film based or digital cameras may be treated for calibration.

2. BACKGROUND

The rapid acceptance of digital cameras range across the photographic industry from the low-end, 35 mm, hand-held camera to the special purpose, mapping camera. At the low end, digital cameras offer advantages over the traditional film based cameras for purposes of measurement applications. Digital advantages in range of light sensitivity (speed) over a wider spectral response, and immediate access to imagery, are well known. For measurement applications, the digital camera provides a direct means of recovery of the internal orientation since its basic character provides a known and stable relationship between the lens and the captured image. As a consequence, there is now a growing interest in use of digital cameras for measurement applications, generating a need for an efficient and relatively inexpensive means of camera calibration. This need has recently been met by the USGS facility for camera calibration located in South Dakota.

For the cameras intended for aerial surveying and mapping applications, both digital and film-based, the introduction of added sensors such as GPS and INS require careful consideration be given to a systems approach to calibration to assure the added sensors are fully exploited metrically.

In recognition of this need, the United States Geological Survey (USGS) awarded a grant to provide and demonstrate a means for camera system calibration for the aerial mapping camera. During the course of the contract a Nikon D1X camera equipped with wide angle and narrow angle lenses was flown over a specially developed camera calibration range. Trimble GPS receivers controlled the imagery in the air. In addition, film-based photography was collected by a Zeiss LMK 15/23 camera, also controlled by GPS receivers. Programs were developed for image measurement and subsequent camera calibration using Visual C++ software, During the course of this development, a number of interested organizations participated in addition to the USGS. The software development was a cooperative program between The Ohio State University and the University of Calgary with a grant from USGS. The Madison Test and Calibration Range was developed and maintained by the Ohio Department of Transportation / Aerial Engineering Office. Flight testing of the digital cameras was accomplished by Topo Photo, Inc. of Columbus, Ohio.

2.1 *In situ* Approach to Calibration

In a benchmark publication by Eisenhart (1962), found in the Proceedings of the National Bureau Standards, a rationale for the calibration of measurement systems is set forth. His work provides clear guidance for designing and applying a calibration program for the airborne sensors associated with the aerial mapping industry. To summarize Eisenhart's concept of calibration:

- Establish first the *"Measurement System Specifications"*
- Exercise the measurement system as specified and compare results to a standard of higher accuracy until sufficient information is available to achieve a *"State of Statistical Control"*

The system specifications describe all aspects of the system including hardware, software, environment of the system and operational procedures necessary to achieve the final measurement. Procedures may include specified ranges within which the system will operate. In the aerial case, for instance, a range in altitude can be specified that, by its definition, represents an important practical aspect of the concept.

By accepting the concept of measurement system calibration, it is clear that certain aspects of camera calibration, as traditionally practiced, need to be reconsidered. For the aerial camera, independent of the added sensors, the primary difference in measurement accuracy for application is due to temperature differences between a laboratory and an *in situ* method of data collection. This difference is most evident for an open-port windowed aircraft, most typical of the aerial industry. For the closed-port, the addition of the window adds an additional optical component to the system not conveniently treated during the laboratory approach to calibration.

Experimental data collected under applicational circumstances tend to support the need for adopting an *in situ* approach to the calibration of the aerial camera.

For the aerial case, the choice of camera platform, as with digital cameras, offers a wide range of possibilities with the technically best being the most expensive. The choices, discussed below, range from the minimum cost, single-engine, open-port aircraft to the multi-engine, windowed-port aircraft.

2.1.1 Single-Engine Open-Port In the United States one popular, relatively inexpensive, aircraft is the Cessna 207. The aircraft represents an adequately stable platform for carrying the camera, mount and supporting equipment. However, when considering use of airborne GPS for survey control, one must assume that a significant disturbance is generated in the volume of air below the aircraft through which the camera must function. The engine exhaust may be diverted, however, the cooling air for the conventional reciprocating engine can cause a rise in temperature from external ambient to cowl exit of 66^{o}C. In addition, as with all open port systems, the influences of temperature differences between cabin and external air will have an influence on the metric characteristics of the camera.

2.1.2. Multi-Engine Open-Port Probably the most widely used aircraft for colleting photography of photogrammetric quality is a light twin, open port platform. With this aircraft, no significant disturbance to the volume of air beneath the aircraft is expected. However, the influence of the temperature difference between cabin and outside air can be extreme. The difference causes a change in relationship between the optical and image collecting components of the aircraft. This change usually is seen as a centering error that can be represented as a corresponding change in the camera constant. Accordingly, recording temperatures within the cabin and at the camera lens may become a means for accounting for the open port installation errors.

2.1.3. Multi-Engine Windowed-Port The ideal, but most expensive aerial platform includes a windowed port. The window consists of high quality glass as specified by military standards and others. Clearly, in application, the window becomes part of the optical system and must be included as part of the photographic system during calibration. When operating without cabin pressurization, the influences of temperature differences are mitigated. When pressurized, the differences between cabin and external pressure generates a stress/strain relationship on the window, producing an image deformation, that requires additional mathematical modeling during the calibration process (a component of the system specification).

3. USGS/OSU PROJECT

The USGS project is viewed as an initial step leading to a means of camera system calibration on a national basis. Software was developed for the image measurement process and for the subsequent computation of interior orientation, the primary components of the camera calibration.

Subsequently, a series of flights were conducted over the Madison range to verify the systems approach to camera calibration for both the digital and film-based cameras.

3.1 Software Development

The programming, accomplished in Visual C++ language, resulted in two programs.

3.1.1 Image Measurement Program The first program, termed "Image Measure" (IM) software, was designed for measurement of image coordinates and production of files for subsequent introduction to the calibration program. The observation of target images is facilitated by computation of a single photo resection after the first four targets have been identified and manually measured. At that point, the program indicates the residuals of the fit to control, and selects only those targets that appear within the current photograph. This is followed by automatic movement of the measurement mark to the first of the imaged targets in the selected set of targets. At this point, the observer can rapidly make the fine pointing, record the image coordinates and is automatically directed to the location of the next target image. The auto-location is accurate to several pixels for a system of low distortion. After all the reduced target list images have been brought forward for fine pointing, the observer saves results and moves on to the next photograph.

For processing of the film-based images, the film is first scanned and the imaged fiducials are measured, followed by a two-dimensional transformation into a fiducial coordinate centered system. All subsequent image measurements on this frame are transformed accordingly, resulting in photo coordinates in a fiducial system but corrected for film deformation. Digital image coordinates are measured directly from the photo file, then transformed by a rigid–body transformation to the photo center, resulting in conventional photo image coordinate system.

Additional input files provide the GPS coordinates of the antenna phase center, the survey coordinates of the targets, the first approximations to parameters of both interior and exterior orientation along with associated variance covariance files for weight constraint purposes.

A right-handed coordinate system and right-handed rotations are assumed in all cases. When all images on a given photo are measured and transformed to photo coordinates, a final single photo resection is computed, resulting in the angles relating the photo coordinate system to the ground system of coordinates. This transformation of coordinate systems proceeds from the object space to the image space. Given the rotation matrix, expressing the relationship of ground to camera coordinate systems, its inverse is used to transform the photo parallel offsets, GPS phase center to camera entrance node, into corresponding components in the ground control system. The exposure station then is computed by addition of the transformed spatial offsets to the phase center coordinates of the antenna.

For any given photo, final processing applies atmospheric refraction correction using the Saastamoinen model (1972). The final step applies the transformed spatial offsets, antenna phase center to camera node, directly to the GPS coordinates for any given exposure. Results of this program are data files containing refined photo coordinates of targets (lens distortions remain) and exterior orientation.

3.1.2 Camera Calibration Program The calibration program titled "Bundle Adjustment with Self Calibration" (BASC) is designed to use the files produced by the image measurement program (PIC). Additional files used by the program include a description of the camera including first approximations to the interior orientation, target survey coordinates, and variance covariance information for all parameters describing interior and exterior orientation, image measurements and target coordinates.

The mathematical model used is the SMAC model as defined by the USGS, a model that represents focal length correction, symmetrical and decentering distortion, and location of the principal point.

In accord with this SMAC model, radial distortion is expressed as: (δx, δy)

$$\boldsymbol{\delta x = (x - x_p)\,(K_o + K_1 r^2 + K_2 r^4 + K_3 r^6\ \ldots)}$$

$$\boldsymbol{\delta y = (y - y_p)\,(K_o + K_1 r^2 + K_2 r^4 + K_3 r^6\ \ldots)}$$

Where: x_p, y_p = photo coordinates of the principal point

$r^2 = (x - x_p)^2 + (y - y_p)^2$

K coefficients representing radial, symmetrical distortion

The distortion due to decentering of the compound objective is expressed as: (Δx, Δy)

$$\Delta x = (1+ P_3 r^2)\,(P_1 (r^2 + 2x^2) + 2 P_2 x y)$$

$$\Delta y = (1+ P_3 r^2)\,(2 P_1 x y + P_2(r^2 + 2 y^2))$$

Where: P coefficients represent decentering distortion

The corrected photo coordinates are then:

$$x_c = x + \delta x + \Delta x$$

$$y_c = y + \delta y + \Delta y$$

Note that the K_o represents a scalar term for photo coordinates. Accordingly, it accounts for small differences in the chosen value of focal length. This permits use of an arbitrary but close approximation when using the nominal focal length associated with the lens design in the computations.

3.2 Flight Test Verification

Flight testing of both digital and film-based cameras was conducted concurrently with the development of the software programs. This assured that all elements of the calibration process could be identified and treated accordingly during development of the programs. It also verified that digital cameras, even with narrow fields of view, can be accommodated by the *in situ* approach to aerial camera calibration. In addition, these flight tests demonstrated the contrast in results between a laboratory and *in situ* form of calibration. These differences further justify the need for a systems approach to aerial camera calibration.

3.2.1 Madison Test and Calibration Range The Madison Range currently consists of about 100 targets located within a 1.6 km by 2.6 km region, 50 km west of Columbus, Ohio. Target coordinates were measured by GPS methods with elevations augmented by spirit leveling. Adjustment results indicate that the internal accuracy of the network is better than 2 cm on each axis and includes the base station, MAD1. The base station is located a distance of 5 km from the range center at the Madison County Airport. The range was constructed and is maintained by the Office of Aerial Engineering of the Ohio

Department of Transportation (ODOT). The Range is centered at latitude 39º 56´ 25” N. and longitude 83º 31´ 28” W. Figure 1. displays the Madison Range.

The targets are painted on existing asphalt roads and are centered on magnetic PK nails. Targets are 2.4 meters in diameter with a 0.80 meter flat white center. The targets were designed to provide optimum images for automatic pointing and recording of image coordinates for film-based cameras flying at about 1200 meters above the field. Figure 2. shows the ODOT personnel as they prepare a standard target on the Madison Range.

In order to image sufficient targets on a single photo, when using conventional digital cameras, targets were densely distributed in the vicinity of the intersections of US40, Potee Road, and Markley Road. In the vicinity of the intersection, targets were separated by 10 meters. As targets radiated from this intersection, the intervals were sequentially increased by the cube root of 2. In this way, relatively narrow field cameras, flying at low altitudes, can acquire sufficient target images for calibration purposes. The target distribution for use by low-flying or narrow field camera systems is shown in Figure 3.

Figure 1. The Madison Test and Calibration Range

Figure 2. ODOT Personnel Preparing a Target

3.2.2 Resection Comparisons to GPS Exposure Station In order to demonstrate the improvements offered by an *in situ* approach to camera calibration when compared to a conventional laboratory calibration, two single photo resection computations were computed using first the results from a laboratory calibration and then computed from results of an *in situ* calibration. The exposure station coordinates for each case were compared to the station coordinates derived from GPS. The concept is indicated in Figure 4.

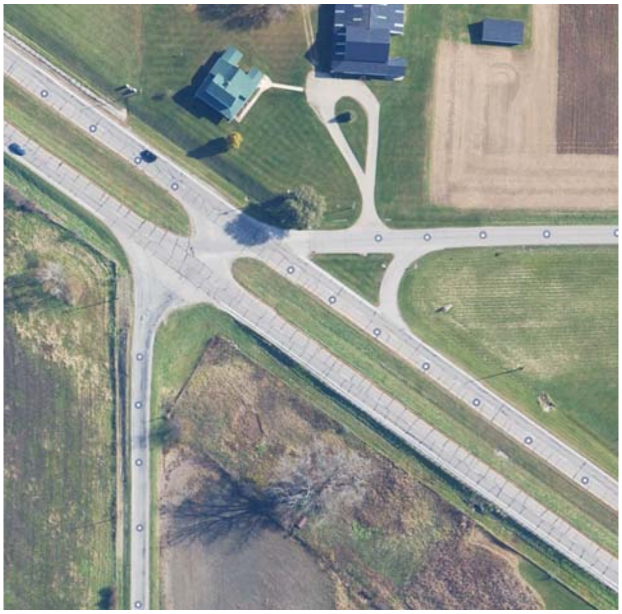

Figure 3. High Density Range for Digital Cameras

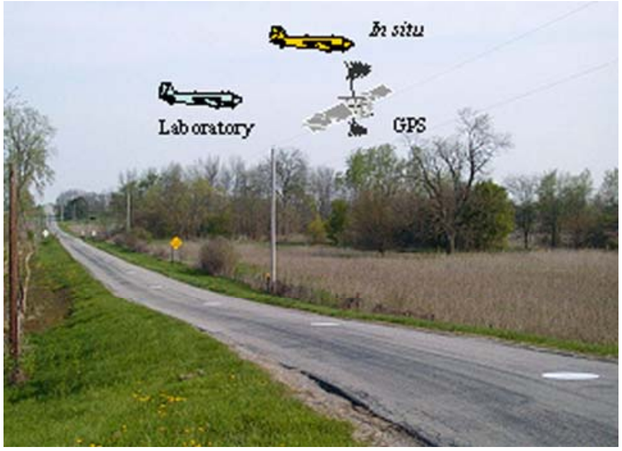

Figure 4. Resected Exposure Stations Compared to GPS Results

3.2.3 Flight Tests of the Zeiss LMK/15-23 Camera In Open -Port Aircraft

The standard film-based mapping camera was flown in a Patenavia light twin aircraft equipped with an open port (see Figure 5.)

Figure 5. Partenavia Light Twin Aircraft with Open Camera Port; Pilot Pete Hobstetter and Photographer Eduardo Kroman

The comparison of results obtained from single photo resections based on laboratory and *in situ* calibrations compared to exposure station coordinates provided by GPS are presented in Table 1. The differences in resected elevations [Z] from those provided by GPS are clearly seen in Table 1. These differences are produced by what may be termed a *centering error*, an error that may be corrected by choice of an appropriate value for calibrated focal length. It is also interesting to note that both calibrations produce nearly the same horizontal components of RMSE and bias.

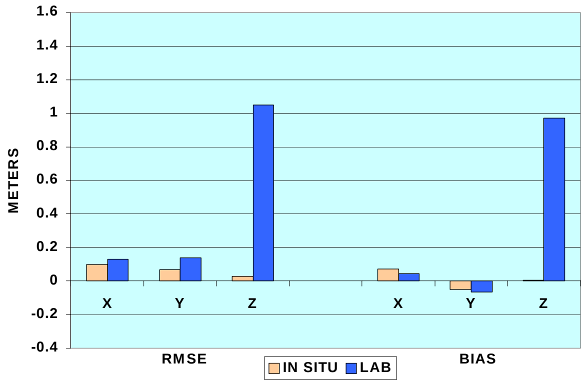

Table 1. Single Photo Resection Comparisons for an Open Port, Twin Engine Aircraft [LMK 15/23 Camera] at 1260 Meters AGL for Seven Photographs

Table 2. provides comparisons for the same aircraft under the same circumstances but at a higher altitude above ground. The resected results at 3070 meters are the same as those for 1260 meters except for the magnitude of the centering error, due in part to the differences in scale of the imagery.

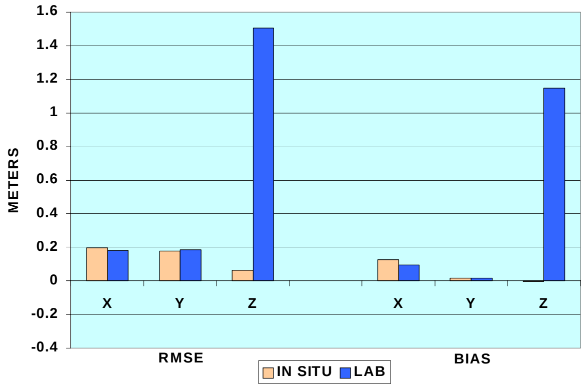

Table 2. Single Photo Resection Comparisons for an Open Port, Twin Engine Aircraft [LMK 15/23 Camera] at 3070 Meters AGL for Nine Photographs

3.2.4 Flight Tests of the Wild RC30 Camera in a Windowed-Port Aircraft

To demonstrate the influence of a port window on results of resection, the NOAA Cessna Citation aircraft was flown over the Madison Range at two different altitudes. The lower altitude did not use cabin pressurization, the higher did. The aircraft is shown in Figure 6. while the spatial offsets, antenna phase center to camera entrance node, are being measured at the Springfield, Ohio airport.

Figure 6. Window Ported NOAA Cessna Citation Undergoing Spatial Offset Measurements at Springfield, Ohio

At the lower altitude of 1316 meters above ground level, no pressurization is normally used. Table 3. indicates the character of the window's influences. When no pressurization of the cabin is used, the window tends to introduce a moderate centering bias and a small increase in RMSE. This is probably due to the inability of the mathematical model used for calibration to represent the deformations of imagery introduced by the window.

The influences of cabin pressurization for the higher altitude flight is indicated in Table 4. Of particular interest in the pressurized case is the inability of the calibration model to account for image deformations for both the *in situ* and laboratory procedures. This is implied by the large bias errors, not only elevation, but also for horizontal components when compared to the GPS result.

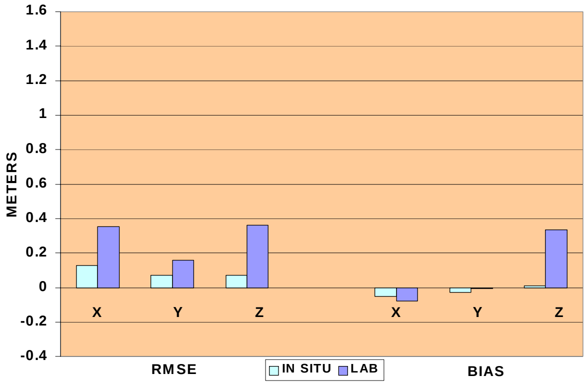

Table 3. Single Photo Resection Comparisons for a Windowed Port, Un-Pressurized, Multi-Engine Aircraft [Wild RC30 15/23 Camera] at 1316 Meters Above Ground for Twelve Photographs

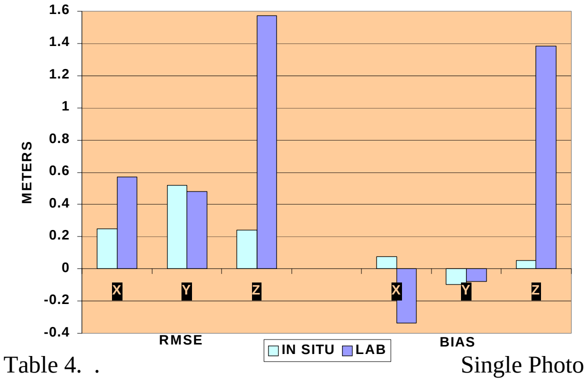

Table 4. . Single Photo Resection Comparisons for a Windowed Port, Pressurized, Multi-Engine Aircraft [Wild RC30 15/23 Camera] at 5817 Meters Above Ground for Five Photographs

4. CONCLUSION

The recognition of significant differences between laboratory and *in situ* methods of calibration, and the preparation of appropriate software to conduct an *in situ* calibration has taken the USGS closer to achieving a means of calibration that can effectively accommodate the added airborne sensors such as GPS.

The Eisenhart concept of "**measurement system calibration**" provides guidelines that can be adapted well to calibration of the aerial camera and its supporting equipment and procedures. The results of an *in situ* calibration represent one element in the "**measurement system specification**". It would remain to establish a "**state of statistical control"** through an ongoing process of testing the measurement system by comparison to a standard of higher accuracy such as provided by a calibration and test range.

We acknowledge with thanks the support given by the USGS to this research and development program. In addition, recognition and thanks are given to the Aerial Engineering Office of the Ohio DOT for range preparation and film based camera flight tests, and to Topo Photo Inc. for conducting flight testing of the digital cameras.

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