AERIAL CAMERA METRIC CALIBRATION – HISTORY AND STATUS

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ABSTRACT

There is a need in this country to establish a broadly accepted method of airborne camera calibration. Accordingly, the ASPRS/PDAD has established a temporary sub-committee to develop consensus regarding methods of geometric and radiometric airborne camera calibration. This paper provides a history of camera calibration in the United States and leads up to current activities in connection with establishment of draft specifications for calibration of both film-based and digital aerial cameras. In addition, there is a comparison of geospatial accuracies of camera resected exposure station coordinates to those provided by GPS. Conventional laboratory and *in situ* methods of calibration are compared. The current draft of guideline specifications for calibration has been submitted to the ASPRS Board for review.

KEYWORDS: camera, calibration, *in situ*, laboratory, aerial, geospatial, accuracy

INTRODUCTION

With the introduction of GPS spatial positioning of the airborne camera exposure station, the possibility of camera calibration based on operationally acquired photography became practical. This approach, usually referred to as an "***in situ***" approach to calibration, is in accord with the specifications for the calibration of measurement systems as defined by Eisenhart (1963).

The aerial photogrammetric system lends itself well to Eisenhart's concept of calibration. When compared to the traditional methods of calibration based on a refined laboratory approach, the *in situ* approach can account for several operational environmental circumstances that are not present in a laboratory approach to camera calibration. The primary environmental difference, when operating from an open ported aircraft, is **temperature**. If a window is used to control the camera environment, the window is not included as part of the laboratory calibration.

Geospatial accuracies of photogrammetric procedures based on both laboratory and *in situ* methods of aerial camera system calibration will be discussed along with history and current status of metric camera calibration.

History of Metric Camera Calibration:

The purpose in this section is to present a brief background on the development of aerial camera calibration in the U.S. leading to the present method used by the USGS for the film-based camera. This will be followed by comments regarding the development of the *in situ* approach for both film-based and digital camera calibrations and progress toward their acceptance.

An extensive discussion of the development of laboratory based calibration is provided in the ASPRS Manual of Photogrammetry, Third Edition (1966). The National Bureau of Standards led the effort to establish a photographic approach to calibration. As the importance of photogrammetry developed both for military and civil applications, other government agencies and organizations made contributions to methods of calibration. Among these were U.S. Naval Photographic Interpretation Center (Stellar Techniques), U.S. Air Force (USQ-28 sub-system, KC-6A camera), Fairchild Camera Corp. (camera production quality control), and USGS (multi-collimator for wide angle and super-wide angle camera cameras).

Responsibility for calibration of cameras used primarily for national photogrammetric calibrations was assumed by the USGS in early 1950s. The photographic multi-collimator method, well developed by the National Bureau of Standards, and now adapted for production, was selected by USGS for this purpose.

The concept of the multi-collimator approach is based on use of two banks of optical collimators, each collimator set in a bank (plane) at angular increments of 7.5 degrees. The two banks are arranged at 90 degrees to one another. All collimators are directed to a central point of reference, the point occupied by the entrance node of the camera. This arrangement provides a means of optical control whose images provide an accurate calibration of the film-based camera, including platen, cone and lens components. This is accomplished under a well-controlled laboratory environment.

Alternative Methods of *in situ* Aerial Camera Calibration:

An outstanding experiment in airborne camera calibration was reported by D. Brown (Brown, 1969) working with the Fairchild KC-6A camera operating within the USAF USQ-28 Geodetic Sub-System. An RC-130 aircraft, operating over the McClure range in northern Ohio, was equipped with a strobe flash coordinated with the exposure of the camera. The photography was collected at night by using ground based stellar cameras oriented against a star background to measure the exposure station locations. Geospatial accuracy results for this film-based (reseau) camera approached one part in 300,000 of the flight height for the horizontal components and one part in 200,000 for elevation. This firmly established the film-based aerial camera as a potential geodetic tool.

Alternative means of airborne film-based camera calibration have used a strongly three-dimensional control field to force reduction in the functional correlation between focal length and flight height (Merchant, 1972). For this experiment, the third dimension in control was provided by Mt. Graham in eastern Arizona. The density of control was provided by the Casa Grande range in central Arizona. Results indicated a need for range differences in altitude to exceed one half the flight heights to achieve significant functional separation of parameters.

Finally, in 1990, Captain L. Lapine, NOAA Corps, (Lapine, 1990) was able to develop and demonstrate the use of early GPS equipment to position an RC-10 camera carried by a Cessna Citation aircraft over the control field located on the Ohio Transportation Research Center grounds. The success of this approach enabled NGS to map extensive parts of the eastern Florida coastline, a task that would normally require more extensive resources.

A calibration range was established in Madison County, Ohio by the Ohio DOT, Aerial Engineering office. Successful airborne calibrations of film-based cameras were conducted over the Madison range for a period of about twenty years. These *in situ* calibrations included systems operated by a number of state DOTs including Texas, Indiana, N. Carolina, and Ohio. In addition, NOAA conducted calibration experiments while working through a range of altitudes by using both pressurized and unpressurized aircraft. Examples of results of the *in situ* calibrations will be described in following sections.

CALIBRATION RESULTS FOR AIRBORNE CAMERAS

Results for film-based aerial cameras based on an *in situ* approach will be presented and discussed in the following sections. Results for the airborne digital camera will also be discussed including influences due to wide temperature changes experienced under operational conditions.

Film-Based Camera Experiences

Early work was done by NOAA/NOS Coast and Geodetic Survey (C&GS) Lewis Lapine, James Lucas and Gerry Mader. They demonstrated a fully GPS controlled flight of a Cessna Citation aircraft at 6000 feet over the Transportation Research Center (TRC) range in Marysville, Ohio. **Without** ground control, the results, when compared to targeted known positions, indicated a root mean square (rmse) error of three centimeters (Lapine, 1990). Results are summarized in Table 1. Note that this work made use of early GPS Trimble equipment collecting data on L1 only.

Table 1. Spatial Differences (meters) (Differences between GPS-controlled aerial photogrammetric positions obtained **without** use of ground control compared to known, targeted ground positions from an altitude of 1830 meters (6000 feet) [Lapine, 1990])

	Aerial Calibration (*in situ*)			Laboratory Calibration		
	X	Y	Z	X	Y	Z
Mean(bias)	-0.001	0.005	**-0.065**	0.081	0.090	**0.704**
Std. Dev.	0.033	0.028	0.085	0.371	0.429	0.180
rmse	0.032	0.028	0.106			

North Carolina, also working in cooperation with NOAA/NOS, accomplished an aerial calibration over the Ohio TRC with a Wild RC-20 camera in a Cessna 404 aircraft. Results are summarized in Table 2. Further work, under the guidance of John Sherbert, Cecil Hinnant, Keith Johnston and Carl Storch of the North Carolina Department of

Transportation also included a demonstration project flown in November of 1990 in the mountainous region of the Morganton/Lenoir area of North Carolina [Johnston, Storch, 1991]. Results of this work clearly indicated that **without** use of ground control, spatial accuracies could be obtained to produce maps at a scale of 1:600 (1 inch to 50 feet) and two-foot contour intervals.

Table 2. Spatial differences (meters) (Differences between GPS-controlled aerial photogrammetric positions obtained **without** use of ground control compared to known, targeted ground positions from an altitude of 1830 meters (6000 feet) [Johnston, Storch, 1991])

	Aerial Calibration (*in situ*)			Laboratory Calibration		
	X	Y	Z	X	Y	Z
Mean(bias)	0.041	-0.014	**-0.036**	-0.037	0.031	**-0.636**
Std. Dev.	0.034	0.040	0.073	0.179	0.194	0.073
rmse	0.052	0.042	0.080	0.179	0.179	0.640

Film-Based Camera Experiences at the Madison Range

The Madison Calibration Range was located 50 km west of Columbus with targets located on US-40, I-70, Old Columbus Rd. and Potee Rd. One hundred targets consisting of a painted 1.4 meter diameter flat black circle and a 0.8 meter flat white circle were painted on asphaltic road surfaces. Targets were located by the ODOT Aerial Engineering using GPS. Figures 2A and 2B indicate targeted road layouts and large scale images of targets. Target centers were located to accuracy (standard error) of 2 cm in X, Y, and elevation. The range was prepared and maintained by the ODOT, Office of Aerial Engineering.

Figure 2A. Madison Range Layout

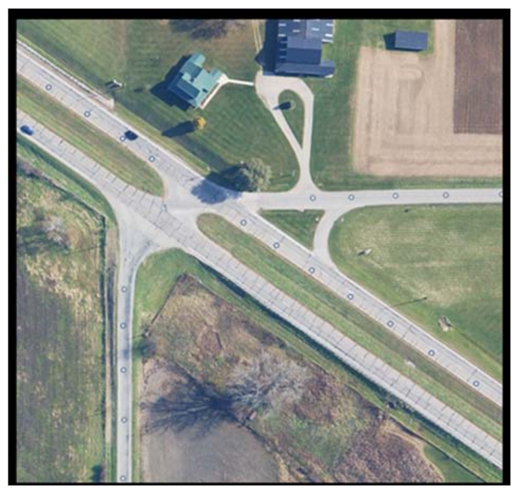

Figure 2B. Typical Targets

Geospatial Accuracy Testing

If one accepts the geospatial accuracy of GPS when assigning coordinates to exposure stations as a high accuracy independent standard of position, then a spatial accuracy assessment can be made by comparing photogrammetric resected coordinates (Xo, Yo, Zo) to those provided by GPS. Results of resection comparisons to GPS, using either a laboratory or *in situ* based calibration, are presented in the following tables. The concept is shown in Figure 2C.

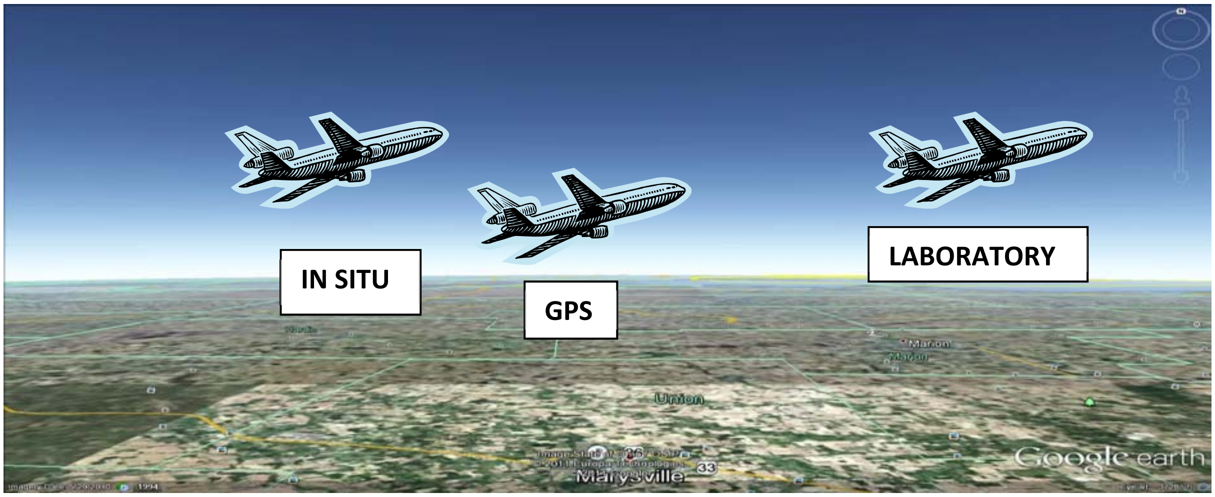

Figure 2C. Resected Exposure Station Coordinates Compared to GPS Results.

Open-Ported Light Twin

The open-ported light twin is well suited to large scale mapping applications. The issue of possible distortions introduced by exhaust and engine cooling is essentially eliminated by moving the camera forward from a view through these disturbances. An example of such aircraft is the Partenavia Observer as seen in Figure 2D

Figure 2D. Ohio Department of Transportation's Partenavia Observer and Crew.

Results for Open-Ported Twin at 1260 Meters AGL

A comparison of exposure station coordinates (Xo, Yo, Zo) determined by single photo resection and orientation computation (SPRO) for both a laboratory and *in situ* calibrations when compared to the corresponding coordinates produced by GPS, is provided in Figure 2E. Of particular note is the extreme elevation bias introduced by use of a laboratory calibration as compared to an *in situ* approach. It will be shown below that this bias is primarily introduced by temperature differences between those of the operational and laboratory environments. The root mean square error (rmse) in elevation introduced by the laboratory calibration amounts to one part in 2,800 of the flight AGL as compared to that of the *in situ* approach which is one part in 30,700. The difference in results is clearly introduced by bias components of the comparison to the GPS results.

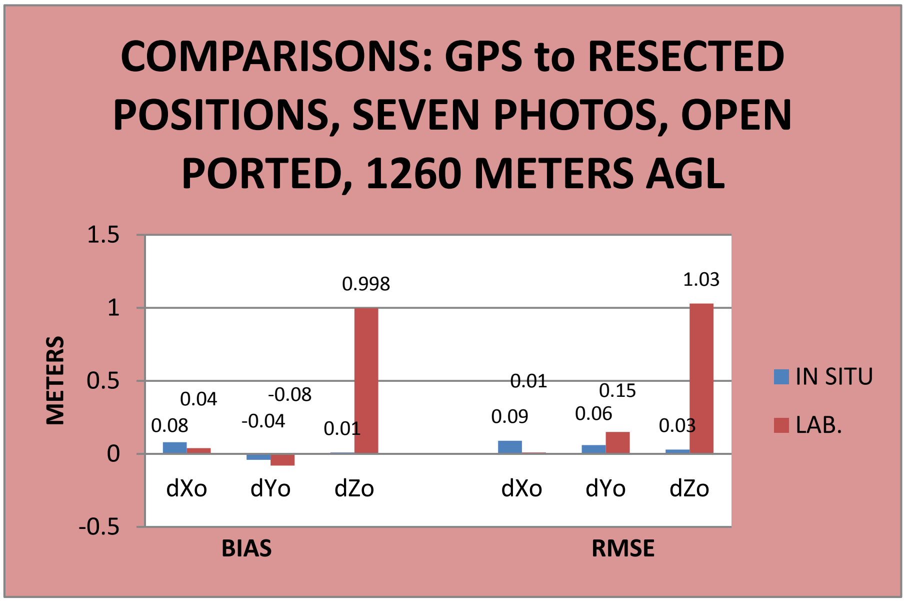

Figure 2E. Open-Ported Results for 1260 Meters Above Ground Level (AGL).

Results for Open-Ported Twin at 3070 Meters AGL

The influence of environment on calibration appears to be proportional with increase in altitude and thus temperature as seen by comparisons of Figure 2E to Figure 2F.

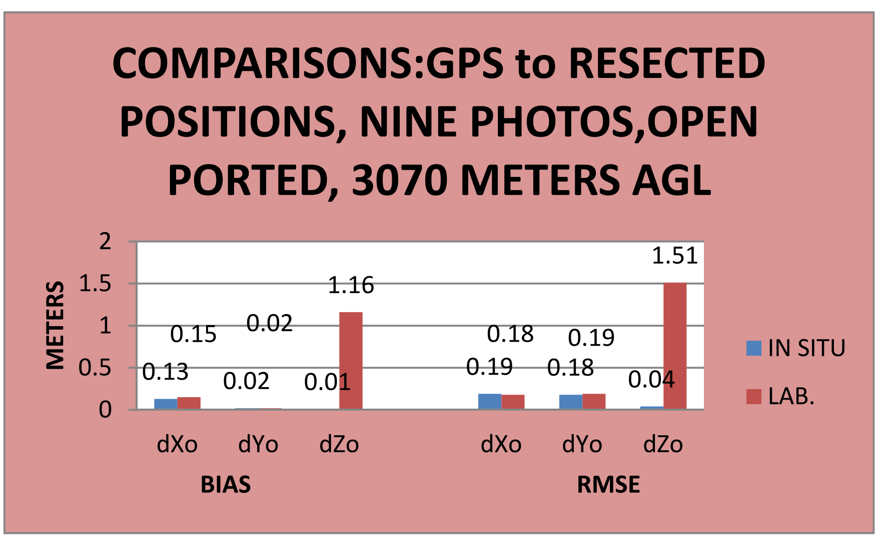

Figure 2F. Open-Ported Results for 3070 Meters Above Ground Level (AGL).

Window-Ported Aircraft

The window-ported aircraft is usually reserved for high-altitude applications. Here, temperature differences are of less concern than pressure differences. Typically, cabin pressurization begins at 6000 feet, causing a pressure difference as the aircraft gains altitude. Deformation of the glass window can be expected. Some results of changes in calibration with pressurization are presented in the following sections.

Figure 2G shows the NOAA citation aircraft in a stabilized condition while spatial offsets are being measured. For subsequent applications, these spatial offsets, measured parallel to the photo coordinate axes, are necessary to relate the GPS Antenna phase center to the camera lens entrance node.

With the window in place but without pressurization, primarily the window's influence is added to the laboratory calibration at an altitude of 1613 meters AGL. This is seen in Figure 2H.

Figure 2G. NOAA Window-Ported (Pressurized) Cessna Citation Stabilized for Spatial Offset Measurements, to Phase Center to Entrance Node.

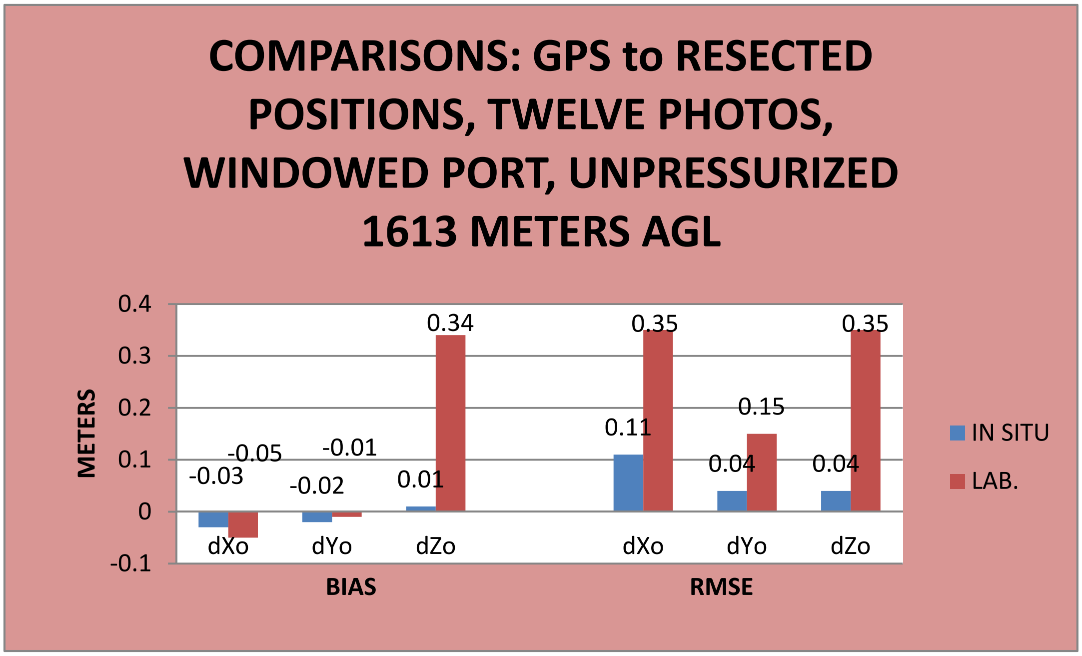

Figure 2H. NOAA Window Ported (unpressurized) at 1613 Meters AGL

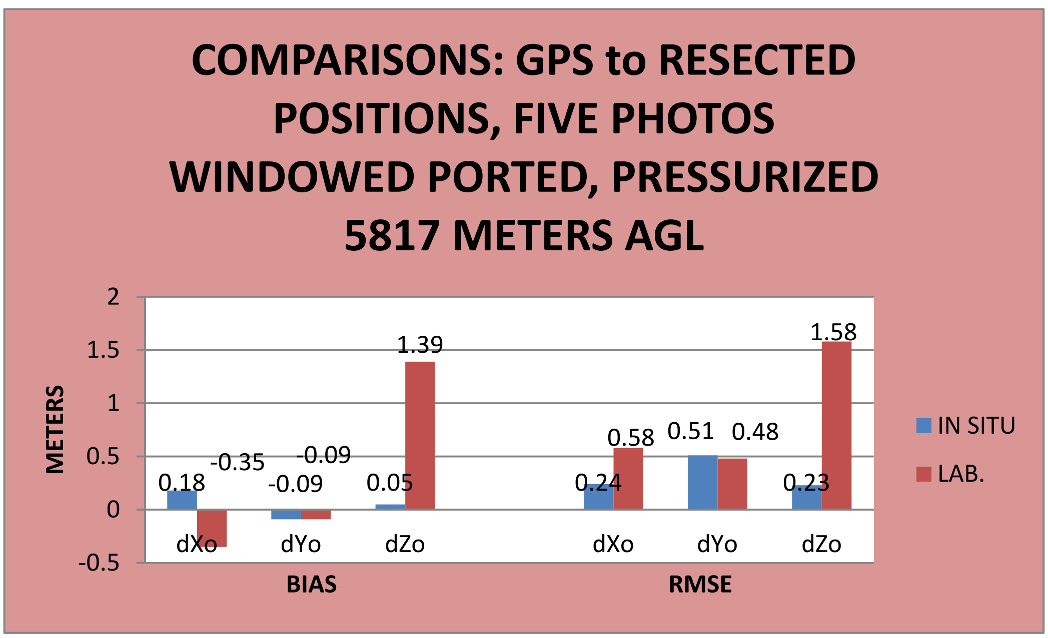

Figure 2I. NOAA Window Ported (pressurized) at 5817 Meters AGL

Results for the pressurized system clearly indicate the influence of cabin pressure on the flatness of the window. Window distortion was caused by a uniform load on a rectangular glass window, even though the window was designed to resist deformation due to pressure. The results caused by cabin pressure on window deformation are indicated in Figure 2I.

INFLUENCE OF TEMPERATURE ON *IN SITU* CALIBRATIONS:

Most non-military airborne camera platforms use an open port to avoid the cost and weight of a suitably flat window. Accordingly, the cameras are subject to large differences in temperature under operational circumstances as compared to those of the calibration laboratory.

This influence was investigated by Topo Photo Inc. with USGS support (Merchant, 2006). During this investigation, the nominal relation of changes in temperature (C) and change in focal length were determined to be about one part in 2000 for a typical, low altitude, operational mission. This error corresponds to a one meter, systematic difference in elevation between the camera and the GPS, for photography flown at 2000 meters above ground.

Results for this investigation are shown in Figure 3A and Figure 3B. A similar result should be expected for conventional mapping cameras. This suggests that records of calibration taken over time and temperature differences should be kept by a recognized central agency. Values for focal length could then be determined for any specific camera as a function of operational temperatures.

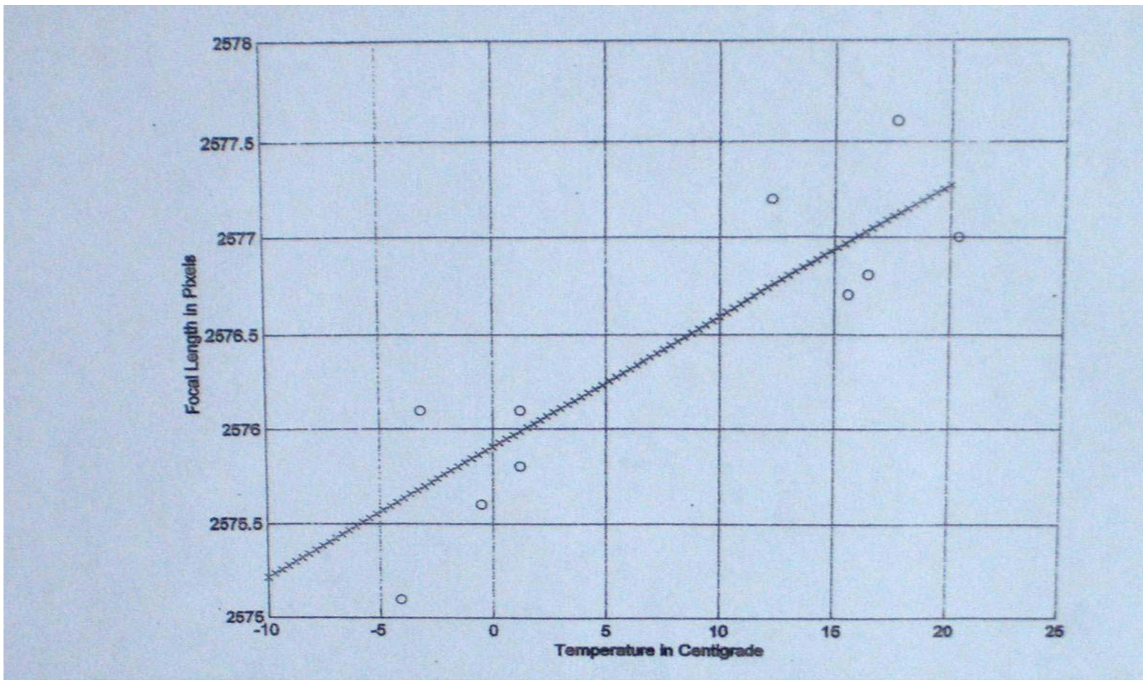

Figure 3A. Linear Fit of Calibrated Focal Lengths as a Function of Outside Air Temperature.

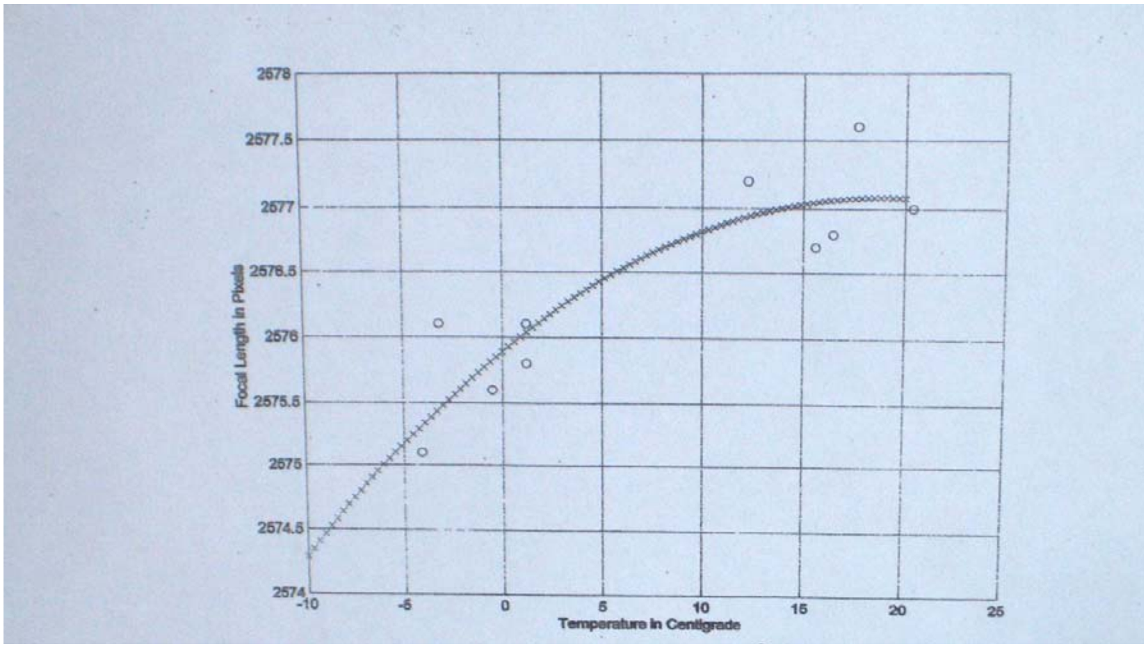

Figure 3B. 2nd Degree Fit of Calibrated Focal Lengths as a Function of Outside Air Temperature.

IN SITU CALIBRATION OF THE AIRBORNE DIGITAL CAMERA

The ASPRS/PDAD/Camera Calibration Committee, consisting of those interested in camera calibration [50+ members], was organized at the March 2011 ASPRS meeting in Milwaukee. Since then, the committee has produced draft guidelines for the *in situ* metric calibration of the airborne digital camera. The work has been based on the successful calibration of Midwestern Aerial Photography's Zeiss DMC II camera.

Concurrently, with the development of guidelines for calibration, guidelines for design of what is termed "Crossroad Range" have been produced. This range can be established on flat terrain and be designed for flight altitudes ranging from several hundred to 20,000 feet. All that is required is roads crossing at a nominal ninety degrees and preferably consisting of good quality asphaltic surfaces. These surfaces allow for use of well-established DOT methods of marking quality targets in an efficient manner.

The calibration guideline draft is currently being processed in a manner prescribed by the ASPRS/Professional Practice Division for establishment as ASPRS guidelines.

Summary of Calibration Results for the Zeiss DMC II 140 Digital Camera

The calibration was accomplished by using digital aerial photography flown in an Aztec aircraft. Image measurements were made by using the program IM (USGS) and the calibration results were produced by using the program DCALC18 (Topo Photo). Since the interior orientation was determined by Z/I and applied to each photo, only the focal length and position of the principal point were treated as unknown parameters.

Based on a 6 photo solution and observation of 114 controlled target images, the rmse of residuals was 0.004 mm. The resulting calibrated focal length equaled that provided by the factory calibration produced in Germany within 0.001 mm. The position of the principal point differed by 0.003 mm in both x and y. These small differences might well be due to the small differences in camera environment for the two calibrations.

COMMENTS

Development of camera calibration methods have evolved in a logical fashion in the United States to meet the needs of photogrammetrists. Beginning with the research work by Dr. F. Washer and others at the U. S. Bureau of Standards, the photographic multi-collimator method of camera calibration evolved. This laboratory method has severed for many decades as the device and approach used by the USGS to serve both the government and the civil community as a means of camera calibration.

With the introduction of airborne, geospatially accurate GPS, the practical applications of airborne calibration methods (*in situ*) evolved. It then became possible to develop an approach that followed the guidance offered by Eisenhart for the calibration of measurement systems, in this case, the airborne metric camera system.

As these *in situ* methods of calibration developed, it became apparent that certain factors of the operational system were not being addressed by a laboratory approach to calibration. When a laboratory calibration was used to correct imagery, a single photo resection produced elevation differences from the GPS measured elevation amounting to as much as one part in 2000 of the flight height. As was pointed out, proportional errors exceeding one part in 20,000 for elevation closure, is not unusual for a properly (*in situ*) calibrated camera.

Several conclusions can be drawn from the discussions presented here:

- The laboratory based methods of camera calibration have evolved to suit the needs of the mapping community within the limitations of technology available.
- With the advent of practical, accurate airborne methods of positioning the camera at the time of exposure by means of GPS, it is now possible to calibrate the airborne system to improve the geospatial accuracy produced by aerial photogrammetric means. The improvement generally produces an order of magnitude in geospatial accuracy when compared to the laboratory methods.
- The ASPRS should adopt guidelines for *in situ* camera calibration to provide producers and users of aerial photography with the highest quality imagery for geo-spatial photogrammetric purposes.

My thanks go to those who have participated in the ASPRS/PDAD/Camera Calibration Committee and who have provided constructive criticism during the course of development of guidelines for the *in situ* calibration of the airborne camera. It remains, following due course, for the ASPRS to adopt the proposed guidelines for calibration of both film-based and digital cameras.

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