

GUIDELINES FOR THE *IN SITU* GEOMETRIC CALIBRATION OF THE AERIAL CAMERA SYSTEM

These guidelines have been developed by the Primary Data Acquisition Division and the Camera Calibration Committee, and have undergone a formal public review process through ASPRS. The ASPRS Board formally approved these guidelines at its October 28, 2013 meeting.

BACKGROUND

The guidelines provide steps to achieving an airborne camera system metric calibration and have provisions for constructing an *in situ*, cross-road calibration and test range. These steps are based on successful metric calibrations of both film-based and digital aerial camera systems. In order to accurately calibrate a camera system, there are several steps that must be followed before, during and after the data collection flight. These guidelines have been initially limited to rectangular-frame cameras and not push-broom cameras. A report of the calibration's results including calibration parameters and their accuracies should be prepared after the calibration flight. These new guidelines will be helpful to the remote sensing community as film cameras are replaced by digital cameras. The guidelines include examples of *in situ* calibrations of a Z/I DMC II digital camera and of a Z/I TOP film camera as well as for a typical calibration range. The examples include the results of the *in situ* method of aerial system calibration in a summary analysis and calibration report.

In summary, the steps required to accomplish an airborne camera system calibration are as follows:

- Collect detailed information regarding the camera, aircraft, and interface equipment
- Review the flight plan to cover the required imagery in terms of scale and orientation
- Fly the flight plan and return to measure spatial offsets (lens node to antenna phase center)
- Measure the target images and process the calibration data providing results and analysis
- Prepare and distribute the calibration report

1. Purpose

This document is intended to serve as guidance for the processes involved in the airborne *in situ* geometric calibration of vertically-oriented digital and film-based frame type cameras. It has been prepared to assist those who are concerned with airborne applications of both digital and film-based cameras for surveying and mapping purposes. As a system approach to calibration, results are intended for use in geospatial applications that require high accuracy. It is understood that the guidelines provided here represent only one bundle-block adjustment approach to system calibration. In future revisions, these guidelines may expand to cover a broader range of camera and sensor types and include such support devices as the IMU.

These guidelines are concerned with the airborne camera system, which consists of the camera, mount, GNSS, aircraft, and their spatial relationships. Calibration results include both interior and exterior orientation parameter values along with estimates of their accuracies after a bundle-block adjustment. These guidelines also describe pre-flight, in-flight and post-flight processes and suggest a possible calibration range design. Refinements to these guidelines may evolve with future developments to include range specifications.

The guidelines described here are based on a benchmark US Bureau of Standards document by Eisenhart (1963), which provides the concept of measurement "system" calibration. The preparation of these

guidelines was guided by Eisenhart's concept of measurement "system" calibration. When compared to laboratory methods of calibration (i.e., camera only), significant improvements in geospatial accuracies are evident (Merchant et al, 2004).

The concept of "in situ" system calibration for aerial optical cameras has been clearly demonstrated over the last several decades. Today, most final system calibrations provided by aerial camera manufacturers, particularly for digital cameras, are produced by aerial, *in situ* approaches. Examples of geospatial accuracies provided by *in situ* calibrations may be found in Brown (1969), Merchant et al (2004), Cramer (2009) and Merchant (2012). Camera calibration reports provided by digital aerial camera manufacturers also provide a rich source of high quality results. Brown (1969) also provides a benchmark document that develops the concepts and theory of analytical photogrammetry.

2. Conformance

No conformance requirements are established for these guidelines.

3. References

- Brown, D., 1969, *Advanced Methods for the Calibration of Metric Camera, Final Report, Part 1*, DBA Systems, Inc., Melbourne, Fla., 117 p.
- Cramer, M., 2009, Digital Camera Calibration, Official publication of the European Spatial Data Network No. 55, EuroSDR, 262 pp., URL: <http://bono.hostireland.com/~eurohdr/publications/55.pdf> (last accessed 23 September 2013).
- Eisenhart, C., 1963. Realistic Evaluation of the Precision and Accuracy of Instrument Calibration Systems, *Journal of Research of the National Bureau of Standards, C. Engineering and Instrumentation*, Vol. 67C, No. 2, April-June 1963.
- Lapine, L., 1991. *Analytical Calibration of the Airborne Photogrammetric System Using A Priori Knowledge of the Exposure Station Obtain from Kinematic Global Positioning System Techniques*, Ph.D. Dissertation, The Ohio State University, Columbus, Ohio, 188 p.
- McGlone, J. C., editor, 2004. *Manual of Photogrammetry*, 5th edition, American Society for Photogrammetry and Remote Sensing, Bethesda, Md.
- Merchant, D. C., T. Schenk, A. Habib, and T. Yoon, 2004, USGS/OSU Progress with Digital Camera *in situ* Calibration Methods, *Proceedings of XXth ISPRS Congress*, Istanbul, Turkey, TS WG II/1: Real Time Mapping Technologies, pp.19.
- Merchant, D. C., 2012, Aerial Camera Metric Calibration—History and Status, *Proceedings of ASPRS 2012 Annual Conference*, Sacramento, Calif., March 19-23, 2012.

4. Authority

The organization responsible for preparing, maintaining and coordinating work associated with this guideline is the American Society for Photogrammetry and Remote Sensing (ASPRS), and ASPRS's Primary Data Acquisition Division (PDAD) and the Standards Committee.

5. Terms and Definitions

A/C – aircraft

ASL – above sea level

AGL – above ground level

s/n - serial number

GSD – distance measured at the nadir point subtended by one image pixel

GNSS – Global Navigation Satellite System

IMU – Inertial Measurement Unit

L1 and L2 frequencies - Each GPS satellite transmits data on two frequencies, L1 (1575.42 MHz) and L2

(1227.60 MHz)

SMAC – Simultaneous Multi-Camera Analytical Calibration

For additional terms, definitions, commonly used symbology, abbreviated terms and notation see the ASPRS Manual of Photogrammetry (McGlone, 2004).

6. Specific Requirements

Airborne cameras considered by this guideline are limited to the rectangular frame type that provides either digital or film-based images. The digital camera arrays may be treated either as individual arrays or as multiple arrays merged into a common frame. This includes the merging of multi-frames into a common frame (e.g., Hexagon Z/I Digital Mapping Camera (DMC) or Microsoft UltraCam), which is then presented to the user. The linear array (i.e., push-broom) configuration is not currently considered by this guideline.

Observations of aircraft position relative to the calibration field should be made by a GNSS receiver that collects at least L1 and L2 frequencies in a manner useful for post processing. The camera should provide exposure event markers and recorded in GNSS time within an accuracy of 0.0001 seconds, depending on the geospatial accuracy requirements.

The GNSS antenna should be mounted in the vicinity of the vertical projection of the camera's optical axis, limited by the structural requirements of the aircraft. It is preferred, but not required, to use a twin-engine aircraft to avoid possible deformation of the air within the camera's field of view due to engine cooling air stream and exhaust gases.

6.1 Pre-Arrival [before the aircraft and camera system and crew arrive at the airport in the vicinity of the calibration range]

The data provider is expected to equip the aircraft with camera, GNSS and support equipment. In addition to an approved camera system installation, the provider should determine, with the aid of the camera manufacturer, the location of the entrance nodal point with reference to some tangible point on the camera. Finally, the camera system should have a simple exterior temperature measurement device with a probe located in the proximity of the entrance node of the lens.

To ensure that the camera system to be calibrated can be replicated for subsequent application of calibration results, a detailed system specification is to be prepared. This specification should include every element of the measurement system in accordance with Eisenhart's concept of calibration of measurement systems (Eisenhart, 1963). During subsequent operations of this camera system, the provider should assure that the system specifications are applied if the camera calibration results are to be considered reliable.

6.2 Post-Arrival [after aircraft arrives at the range airport]

Measurements should be made to ensure the recorded GNSS data is accurately related to the crossroad target system of coordinates. For a description of the *in situ* calibration ranges, see the Appendix. A bias may exist between the provider's GNSS measurements and in the *in situ* range coordinate system. (Standard methods are available to measure and remove this type of bias.) If a bias exists, it will be applied during data processing as a correction to the GNSS-determined geospatial coordinates of each exposure station.

Finally, the crew should be briefed by someone knowledgeable of the range, who will inform them of the flight pattern over the range prior to the flight. This briefing should also inform the crew, to a limited extent, of the theory of the *in situ* procedure.

6.3 Flight Mission

Image and data collection over the calibration range should be conducted as closely as possible to conditions and procedures anticipated during a typical operational mission. It is understood that some variations may be accepted (for instance, in altitude and temperature). During the photo mission, GNSS observations must be collected at a base station located in close proximity to the range center.

The flight pattern for a typical calibration mission will consist of a minimum of six flight-lines, each acquiring a single frame over the intersection of roads. The directions of the crossroads should intersect at a nominal 90 degrees. No orientation with respect to north is required. Flight directions would then be the following:

- In the direction of the first road;
- In the direction 30° off the first road;
- In the direction 45° off the first road;
- In the direction 60° off the first road;
- In the direction 90° off the first road;
- In the direction 225° off the first road.

These directions are arbitrarily chosen as the minimum number to balance the coverage of target images across the image field and to suppress possible remaining systematic errors not accounted for in the mathematical model. The 45° and 225° directions are to ensure that the maximum number of target images appear in the frame corners. For non-square format cameras, some adjustments to the azimuths may be necessary to cause target images to appear in the extreme corners of the image format.

6.4 Post-Mission [before the data provider's crew leaves the range airport]

Spatial offsets between the phase center of the antenna and entrance node of the camera should be measured. It is essential that these offsets be measured in a coordinate system parallel to the camera coordinate system and to within an accuracy corresponding to those of the exposure station coordinate values. The examples provided in the appendices produce spatial accuracies approximating 2 cm. Accordingly, for these examples, an accuracy of 5 mm along each axis is appropriate for offset measurement accuracies. For other cases of higher altitudes, the 5 mm value may be enlarged linearly. For these measurements, the aircraft must be stabilized on the ground; and the camera's pitch, roll and swing angles measured. Mount angles should be set to zero. These settings facilitate offset measurements along camera axes. These settings, when compared to the nominal swing, pitch and roll angles typical of a photo mission for this aircraft, can be used to measure the spatial offsets between antenna phase center and entrance nodal point of the camera. These comments pertain to both manual and stabilized mounts. It is recognized that operational departures from these values of orientation are a source of system error. To measure these angular values with respect to the aircraft while operational, additional airborne equipment will be required. Note that the IMU, if present, measures camera orientation with respect to the spatial system of coordinates and not the aircraft system of coordinates.

After the flight, it should be verified that the mission has collected adequate and reliable imagery and GNSS data. These procedures, although time consuming, will assure that data processing can proceed and no return of the aircraft and crew will be needed.

Comments from the data provider's crew will be useful in refining all field aspects of the calibration process.

6.5 Data Processing and Reporting

Measurement of imagery and processing of the GNSS data and range coordinates may be conducted by software, commercially available or otherwise. Such software should be capable of using the elements of interior and exterior orientation as added parameters with the possibility of application of appropriate weight constraints. Error estimates after adjustment should be provided along with the estimated standard error of unit weight.

For the final step, a report of calibration must be produced and distributed for subsequent applications. The report should include the specifications describing all equipment and procedures when pertinent (i.e., camera s/n and type, optical filter, film, magazine s/n, processing, scanning, flight height AGL, ASL, temperature at the lens and A/C cabin, and antenna to nodal point spatial offsets).

The mathematical model used to represent the camera's interior orientation will depend on the level of correction applied to the imagery that is provided to the user. In the case of the film-based camera, the user will normally be provided with only the scanned image without corrections. In this case, the conventional SMAC model or another appropriate model may be evaluated during calibration computations that result in estimates of interior orientation including focal length, principle point coordinates and parameters that describe radial and decentering distortions. For a full description of the SMAC model and theory, see (Brown, 1969).

In general, when a digital camera is used, only influences of focal length and principal point coordinates need to be treated as unknown parameters for adjustment purposes. If a parameter is not corrected for in the image provided to the user, it should be treated as an unknown parameter in calibration computations. In all cases, the calibration report must state the mathematical model used to represent the interior orientation of the camera, the estimates of parameter values of the model and estimates of errors in the adjusted parameters. Finally, the source and characteristics of thermal corrections should be indicated when available.

For film-based cameras, the average for all frames of the root mean square error (RMSE) fit of the observations of fiducial marks to their published values should be provided in the report. This will ensure the reliability of fiducial mark stability and data.

The RMSE of image residuals from the calibration adjustment computations results have typically been equal to or less than one-half pixel. The RMSE value of image residuals after adjustment should be indicated in the final report.

7.1 Examples

An *in situ* crossroad camera calibration range specification is outlined in Appendix A, along with an example of the design specifications for a typical camera and flight parameters. Appendix B illustrates the *in situ* method outlined here for a Z/I DMCII digital camera over a calibration range in Plumwood, Ohio, USA along with calibration results. Calibration results for a Z/I TOPO film camera appear in Appendix C. (Calibration examples are courtesy of Midwest Aerial, Columbus Ohio and Topo Photo, Inc., Columbus Ohio).

Appendix A

Crossroad Camera-Calibration Range Specifications

The calibration range is built on any crossroad provided the intersection is a nominal 90 degrees. Roads must have visibility from the air for a distance from the intersection at least equal to the flight height above ground intended for the calibration flights.

Typically, eight targets will be set along each of the four range legs. With the exceptions of the outer several targets of each leg, the spacing variations between targets may be as great as 10 percent. This will permit good site selections for GNSS ground survey purposes.

The following example of design specifications is based on the assumptions of an image pixel size of 14 microns (typical for film-based imagery), a camera with 152.4 mm (6 inch) focal length and a flight height of approximately 600 meters (2000 feet) (AGL). White circular targets of 305 mm (1.0 foot) diameter are centered on a black target of 366 mm (1.2 foot) diameter. A white target on a black road surface will approximate this requirement.

- Nominal spacing of targets in this example is 80 meters (250 feet). (Note: 10% variation of spacing above.)
- Add at least two targets at approximately ± 30 meters (100 feet) on either side of the last outboard target on each leg.
- Control survey should result in a three-dimensional (east, north, up) local coordinate system with the same geodetic datum as that to be used to position the aircraft (WGS84)
- Relative spatial accuracy along each axis should be within 1 cm (0.4 inches) in terms of standard error with respect to the base station(s).

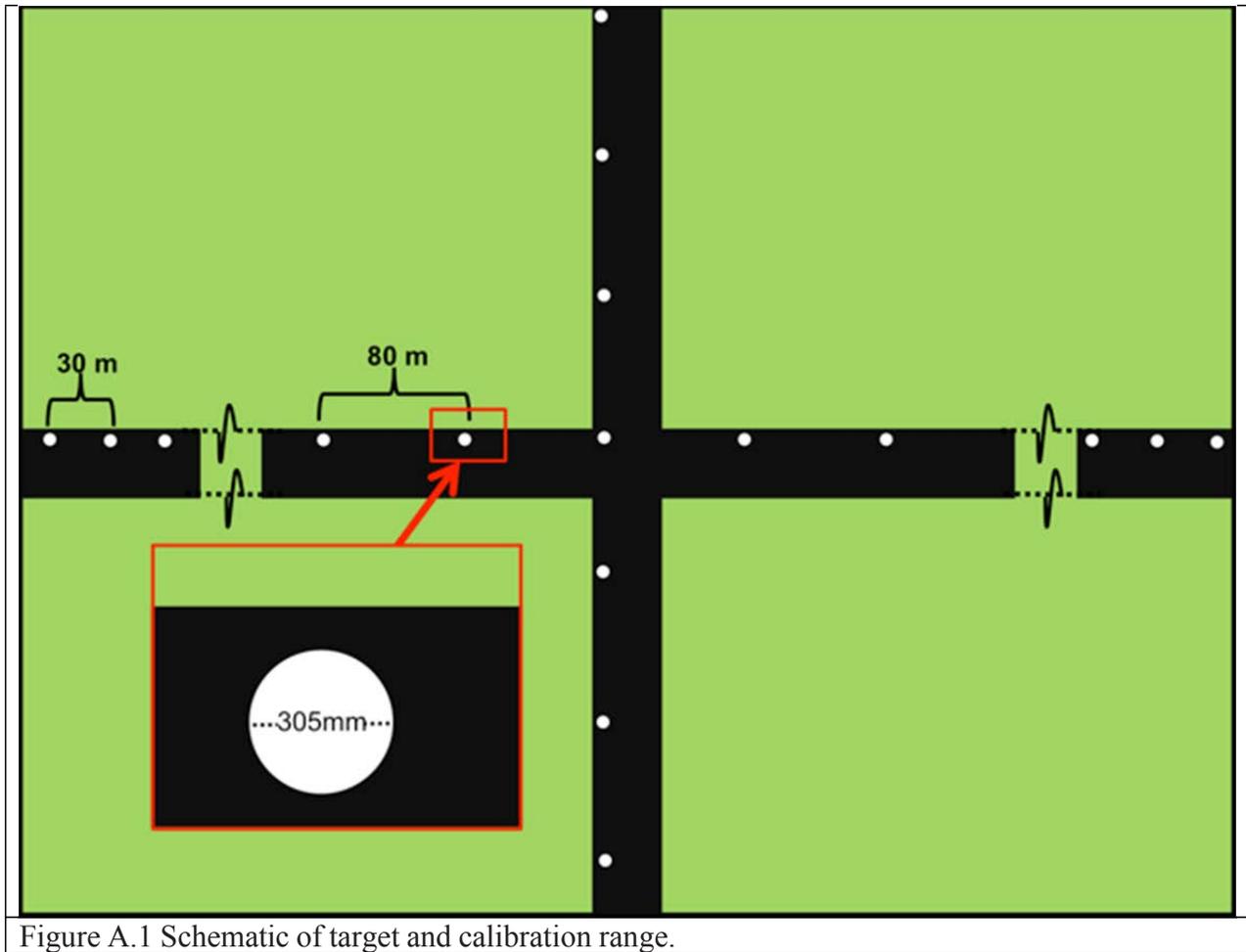


Figure A.1 Schematic of target and calibration range.

For flights of higher or lower altitudes, the linear dimensions should be increased or decreased accordingly. Focal length, pixel size, frame format and camera field angle as they influence target size and distribution should also be considered.

Appendix B

Example of *in situ* method using Z/I DMCII Digital Camera with resulting calibration report.

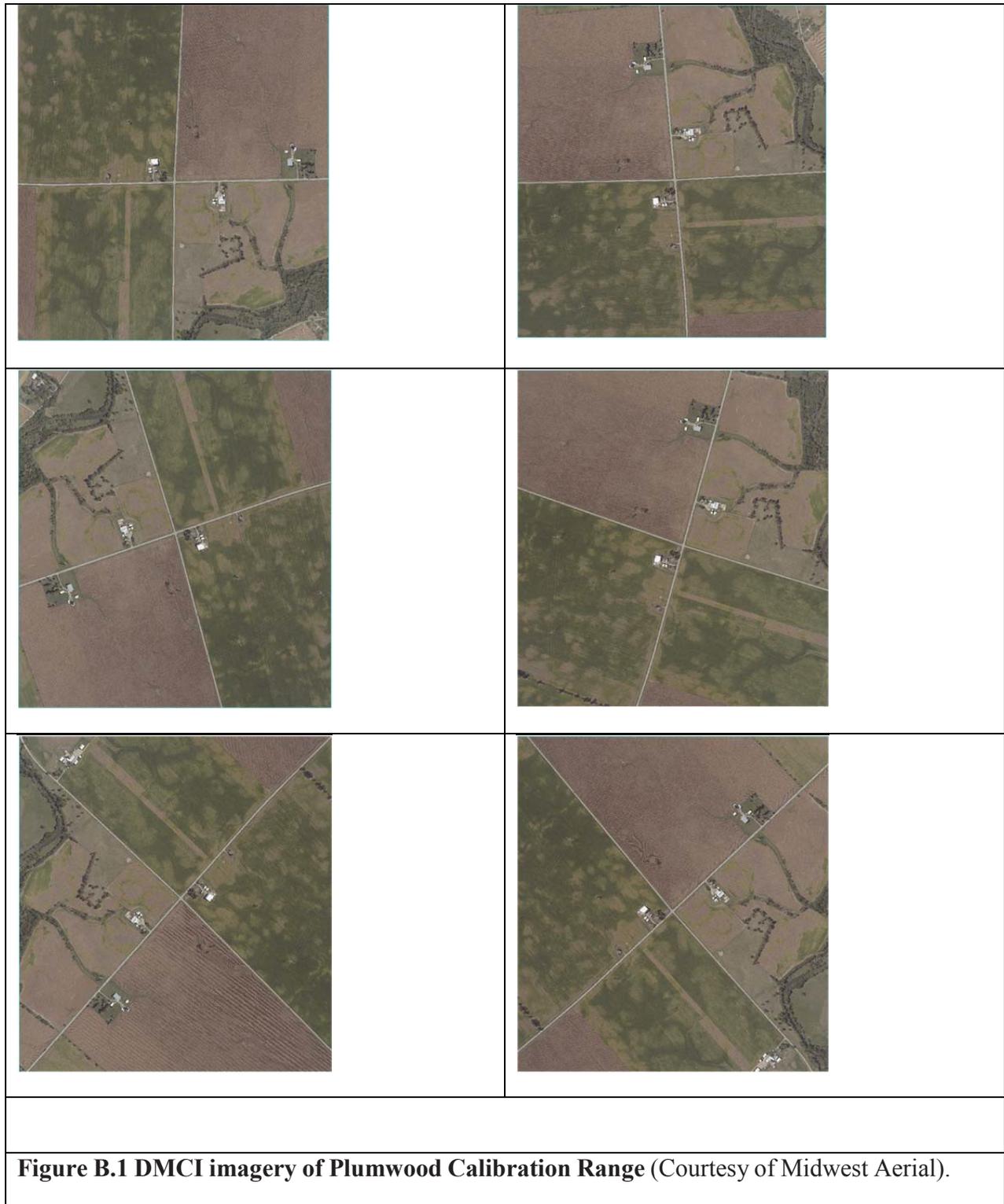
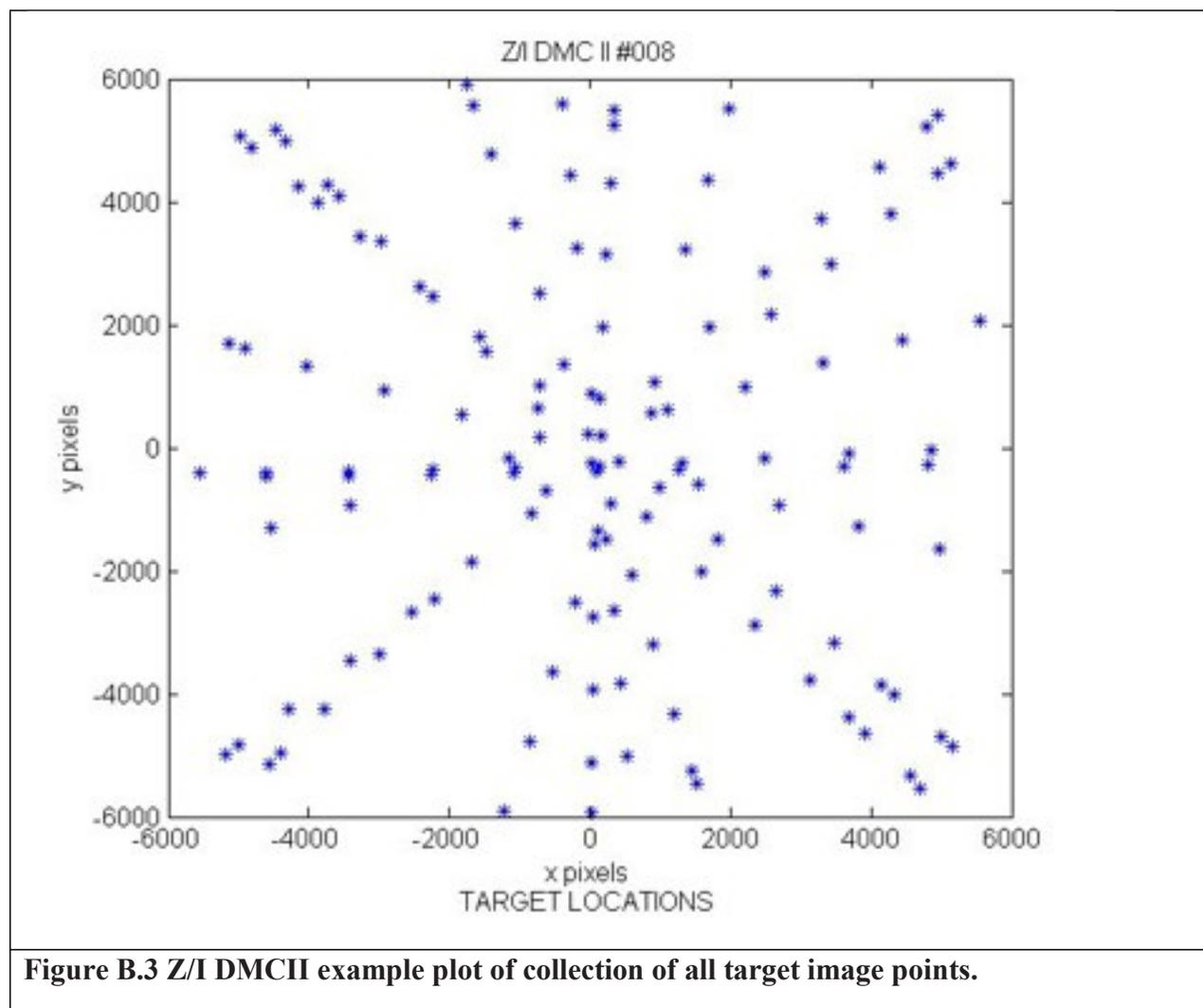




Figure B.2 DMCII targets and associated zooms.



SUMMARY OF CALIBRATION RESULTS

RESULT SUMMARY, IN C:/ CALDAT
TOPO PHOTO, INC.

PROJECT CAMERA B DMC II (Z/I) BODY SERIAL #008 [digital camera]
TOTAL COMPUTATIONAL CYCLES 4
A PRIORI IMAGE STANDARD ERROR ESTIMATE 0.250 pixels

FOR IMAGES ONLY:

NUMBER OF IMAGES OBSERVED: 137. STANDARD
DEVIATION OF IMAGE RESIDUALS: 0.26 pixels
PIXEL (7.2 micrometers)

TOTAL NUMBER OF OBSERVATIONS; IMAGE AND PAR: 391.
TOTAL NUMBER OF UNKNOWN PARAMETERS: 130.
DEGREES OF FREEDOM: 256.

*** STANDARD ERROR OF UNIT WEIGHT *** 1.09

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INTERIOR ORIENTATION RESULTS AFTER 4 CYCLES; [pixels]

PARAMETER	ADJUSTED VALUE	APOSTRIORI STD.ERROR	FOCAL LENGTH	-
0.127785E+05	0.708E+00			
xo	-0.313715E+01	0.482E+00		
yo	0.539371E+00	0.483E+00		

XFRAME = 12096. YFRAME = 11200. MAX. RADIAL = 8242.
IMAGE COORDINATE ORIGIN: x = 6048 y = 5600

[RESULTS ARE BASED ON THE ASPRS GUIDELINES]

Figure B.4 Summary calibration results for Z/I DMCII (Courtesy of Topo Photo, Inc.).

Appendix C

Example of *in situ* method with Z/I Topo Film Camera.

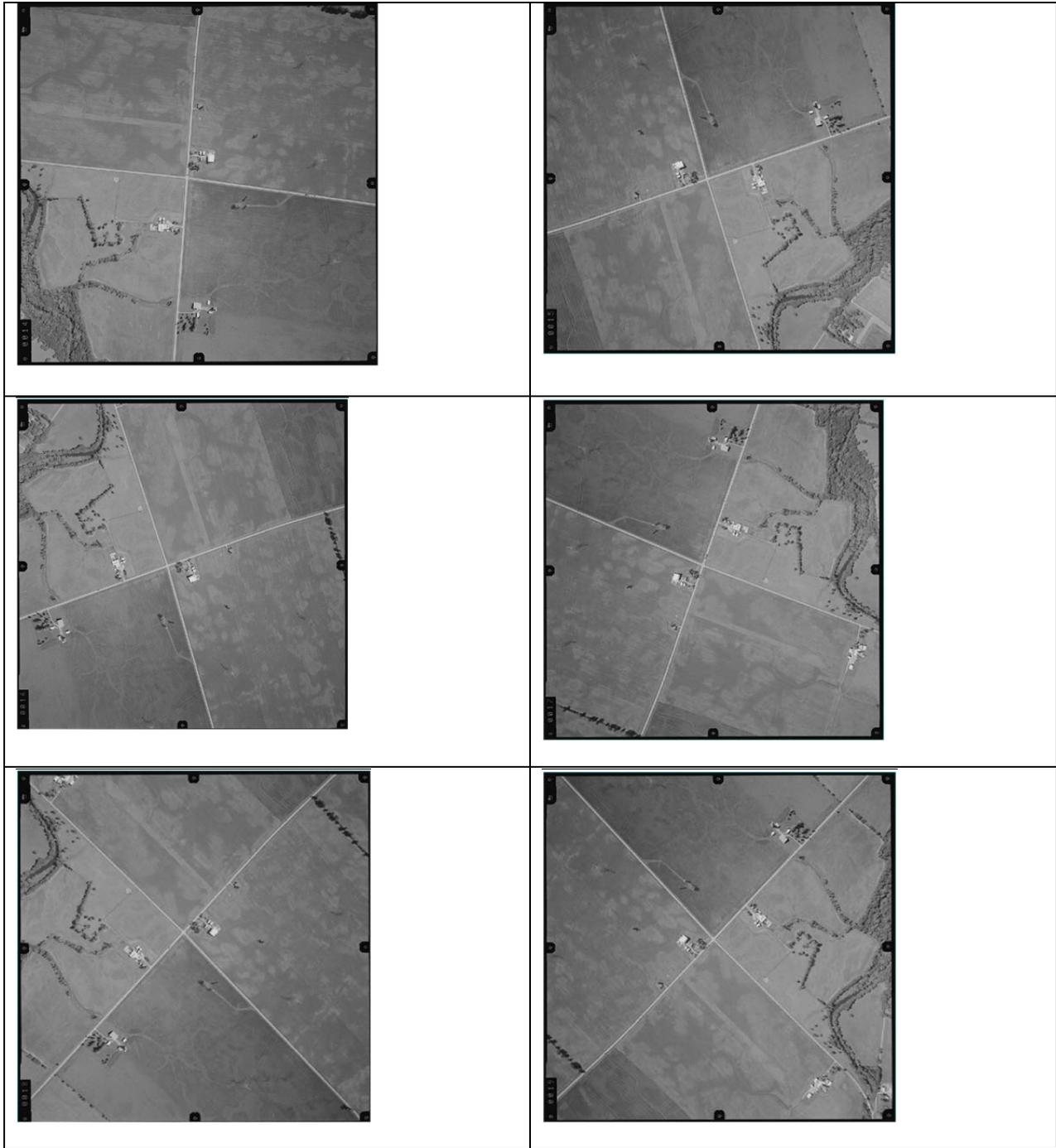
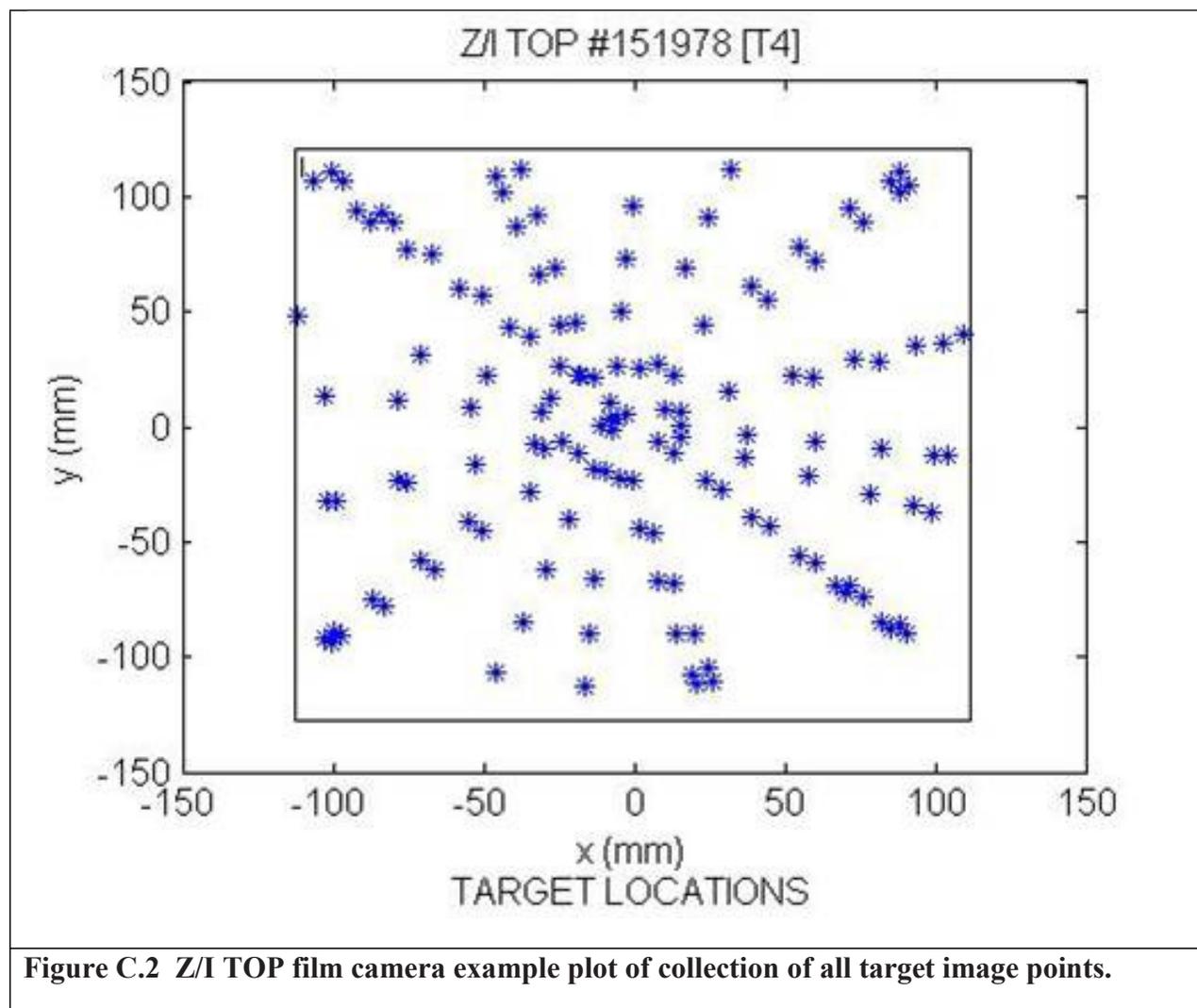


Figure C.1 Z/I Top Film Camera (Courtesy of Midwest Aerial).



SUMMARY OF CALIBRATION RESULTS

PROJECT CAMERA 151978 TOP 4
 TOTAL COMPUTATIONAL CYCLES 4
 A PRIORI IMAGE STANDARD ERROR ESTIMATE 0.006

FOR IMAGES ONLY:

NUMBER OF IMAGES OBSERVED: 140.
 STANDARD DEVIATION OF IMAGE RESIDUALS (mm): 0.0077

TOTAL NUMBER OF OBSERVATIONS; IMAGE AND PAR: 403.
 TOTAL NUMBER OF UNKNOWN PARAMETERS: 135.
 DEGREES OF FREEDOM: 268.

*** STANDARD ERROR OF UNIT WEIGHT *** 1.453

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INTERIOR ORIENTATION RESULTS AFTER 4 CYCLES

PARAMETER	ADJUSTED VALUE	APOSTRIORI STD.ERROR
FL	-0.152830E+03	0.742E-02
xo	0.913467E+00	0.709E-02
yo	0.290035E-02	0.724E-02
Ko	0.0000000	constrained
K1	0.379323E-08	0.974E-08
K2	0.132828E-12	0.902E-12
K3	-0.123845E-16	0.272E-16
P1	-0.258368E-08	0.104E-06
P2	0.105050E-06	0.107E-06

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[RESULTS ARE BASED ON THE CONRADY/BROWN MODEL & ASPRS GUIDELINES]

Figure C.3 Summary calibration results for Z/I Topo Film Camera (Courtesy of Topo Photo, Inc.).