PHOTOGRAMMETRIC CAMERA CALIBRATION

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ABSTRACT

Section 2 (Calibration) of the document "Recommended Procedures for Calibrating Photogrammetric Cameras and Related Optical Tests" from the International Archives of Photogrammetry, Vol. XIII, Part 4, is reviewed in the light of recent practical work, and suggestions for changes are made. These suggestions are intended as a basis for a further discussion.

INTRODUCTION

Society President Commander O.S. Reading pointed out during the sixth congress of the International Society of Photogrammetry held in the Hague in 1948 that it was urgently necessary to standardize test procedures for photogrammetric cameras and to introduce an international system of classification. In the following four-year period, the principal activity of the society's Commission I was the preparation of a specification of methods of calibrating cameras and of measuring their resolution, image illumination, and veiling glare. This preparation was lead by Dr. L.E. Howlett and P.D. Carman of the National Research Council of Canada, President and Secretary, respectively, of the commission. Extensive research for the specification was carried out at that time at the National Research Counsil of Canada and elsewhere. The proposed specifications were discussed intensely at the seventh congress in Washington, D.C., in 1952, accepted in modified form, and reaffirmed by each of the following congresses but the last.

There are many variations in test procedures. Only compromise can bring about acceptance and understanding by all those engaged in calibration activities. The press of work and the need for speed have, in general, precluded close cooperation between the various calibration laboratories. In consequence, many methods of camera calibration have been developed, sometimes with little distinction between calibration procedures. Each method is capable of yielding the information required, but the methods are not all equally simple or capable of handling the same volume of work.

Aerial photography negatives are the foundation of photogrammetry and aerial surveys; hence, their quality will always be of primary importance. For this reason, new test methods will always be developed. In Canada and the United States, the emphasis has been on the photographic method of camera calibration, while in Europe greater emphasis has been placed on visual goniometer methods with the notable exception of the Institut Geographique National in France. However divergent the approaches to the problem of precise camera calibration, the results are similar because all are seeking accurate values to be used in photogrammetry.

Since early 1974, a Working Group on Image Geometry of Commission I, chaired by one of the authors, has carried out the calibration on two front-projected reseau type camera. These cameras were sent to organizations that routinely perform camera calibrations. A total of eleven different methods were used including goniometers, collimator banks, real and artifical stellar calibration, and vertical and oblique aerial photography taken over test ranges. Because of the different methods and a diversity of reporting (Merchant 1977), it was impossible to unambiguously interpret the results or arrive at true comparisons. Hence, the working group has turned its attention to standardizing the parameters describing the geometric-optical performance of a lens/camera system.

Changes to the document now known as "Recommended Procedures for Calibrating Photogrammetric Cameras and Related Optical Tests" (Carman 1961) were made during the following congresses, however, section 2 (Calibration) has been modified only slightly (in 1960) since acceptance in 1952. We believe that certain changes to this section should be made and, therefore, will critically review it subsection by subsection.

REVIEW OF SECTION 2 (CALIBRATION) OF THE "RECOMMENDED PROCEDURES FOR CALIBRATING PHOTOGRAMMETRIC CAMERAS..."

We shall list each paragraph in its present form and discuss it afterwards, where appropriate.

2.1 Calibration should preferable be done photographically under conditions approaching closely those which the camera will encounter in service except that magazine imperfections are excluded. The temperature should be 20°C. A visual method will be permissible if it has been established that it gives the same values as the following photographic method to within the required accuracy.

NOTE: Both systematic and random differences exist between laboratory distortion measurements and the departures from ideal central projection found for a camera in flight. Some causes are curvature of the earth, atmospheric refraction, camera temperature, air pressure, temperature and pressure gradients near the camera and aircraft, lack of flatness of the emulsion, and dimensional changes in the emulsion. For the most accurate work account must be taken of such differences. This can be done from photographs of a test area taken with the camera, the aircraft, and the exposure conditions all the same as in the survey photography or data on the individual effects for the conditions of use can be obtained and combined.

Discussion

The National Research Council camera calibrator (Carman and Brown 1978), the U.S. Geological Survey calibration facility (Tayman 1978), and the U.S. Air Force, Ogden, Utah, camera calibration laboratory use multicollimator test instruments for testing mapping cameras photographically. Laboratory calibration procedures offer a high degree of control of camera mounting, illumination, temperature, air pressure, and targeting. The field test range fly-over method also meets the requirement for photographic type calibration, but does not offer the same degree of control.

The aerial mapping camera is a precision measuring instrument. Although fundamentally an optical instrument, it is dependent, for proper functioning, not only upon proper design but also upon proper performance of a large number of elaborate and complicated mechanical parts, among which are the film magazine by which the film is advanced, constrained to lie flat, and brought in contact with the camera's focal plane frame. For these reasons the U.S. Geological Survey also performs operational type photographic calibrations.

The complete camera system is operated in the laboratory to make film test exposures. From these exposures, contact glass (micro-flat) diapositives are printed. Using these diapositives, measurements are made for calibration and performance evaluation of the lens, camera, and magazine system. The fundamental requirements for any type of camera calibration should be that the negative, when exposed in a magazine, has the same metrical characteristics and accuracy as results from flash plates or goniometer measurements. This method of calibration was brought about by discovery or knowledge of camera/magazine malfunctions that can only be detected by an operational type test. The following are camera/magazine conditions that affect the true calibration of a camera system:

1. Platen not located properly in reference to the camera focal plane frame. The platen pressure may be too great, thus causing platen deformation, or too low, with the platen not seating firmly on the focal plane frame.

2. The height of the focal plane frame with reference to the camera body is not equal on all four sides. This condition can cause the platen to be out of contact with the focal plane frame on one or two sides during the film exposure.

3. Vacuum-induced platen deformation.

4. Malfunction of fiducial mark illumination or data chamber registry.

We recommend that laboratory calibration should include a test of the magazine under operational conditions.

2.2 Definitions

2.2.1 Fiducial Centre: Point of intersection of fiducial axes.

2.2.2 Principal Point of Autocollimation: The centre of the image formed in the emulsion plane by the camera lens from an incident beam of parallel light which in the object space is perpendicular to the emulsion plane.

NOTE: The principal point of autocollimation is the type of "principal point" which can be determined most directly and accurately. Other definitions of principal point have been suggested as partial remedies for inaccurate lens centring. If it is desired to use one of them for some particular application the test data are sufficient to permit its mathematical determination.

2.2.3 Measured distortion: Measured distortion is a vector quantity, being the displacement from the theoretical image point of an ideal camera of the chosen calibrated principal distance to the actual image point for the camera under test. It has as components radial measured distortion and tangential measured distortion. Radial measured distortion is positive when it is outward from the principal point of autocollimation. Tangential measured distortion is positive when it appears as counter clockwise to an observer who is in the image space and is looking toward the lens. The origin for distortion measurement is the principal point of autocollimation. Measured distortion is zero at that point.

2.2.4 Theoretical Distortion: Theoretical distortion is an aberration affecting the position of images off-axis, caused by the fact that objects at different angular distances from the axis undergo different magnifications. Numerically, theoretical distortion is the displacement from the theoretical image point of an ideal lens of the same principal distance to the theoretical image point for the actual lens design under study. It is positive when it is outward from the centre of the field. Theoretical distortion is purely radial and is completely symmetrical. For a perfectly made and perfectly centred lens, measured distortion is equal to theoretical distortion when the position of the image plane and the principal distance are the same in both cases.

2.2.5 Calibrated Principal Distance or Calibrated Focal Length: An adjusted value of the principal distance, chosen so as to distribute the distortion in the manner best suited to the plotting conditions to be employed. The report shall state the way in which the calibrated principal distance has been chosen.

2.2.6 Average Radial Measured Distortion: Average radial measured distortion at any field angle is the average of all radial measured distortions occuring at that field angle. In practice it will usually be adequately determined as the average of the radial measured distortions found for four or more points equally spaced along the circumference of a circle centred at the principal point of autocollimation.

2.2.7 Principal Point of Best Symmetry: The principal point of best symmetry is a point near the principal point of autocollimation chosen so that when it is used instead of the principal point of autocollimation as a new origin for distortion measurement it makes the largest absolute difference between new radial measured distortion and new average radial measured distortion as small as possible along each diagonal of the image format.

Discussion

Cameras with a front-projected reseau and vacuum film flattening (based on pressure differences on both sides of the film resulting from the removal of the air between the back of the film and the magazine reference platen) feature a separation between image plane and reference plane. The image plane is defined as in other cameras by the focal plane frame. The reference plane is no longer defined by fiducial marks located at the image plane but by a net of markings on the lens-element surface nearest to but not identical with the image plane; this surface is plane in the two known types of such cameras, hence, a reference plane exists in addition to the image plane. The separation of the reference plane from the image plane poses the question of which plane is to be used for the determination of principal points of autocollimation and best symmetry, the calibrated focal length, and the lens distortion. Since the two authors differ in their preference in the selection of this plane, no single recommendation will be made.

During the discussions at the 1952 congress, it was suggested that use of the term theoretical distortion be replaced by "the average distortion of a series of cameras of the same model". This is done at the National Research Council of Canada with the definition of lens distortion reference data. We suggest the introduction of a lens distortion reference curve and support the concept of determination of the deviations of the actual distortion of a given lens from that curve. The latter concept would reduce the number of angular positions desirable in calibration, and would avoid extrapolation when the lens distortion cannot be determined to the format corners. An investigation has shown that all lens distortion reference curves ever accepted, or proposed for acceptance, in Canada can be defined by polynomials (Ziemann and El-Hakim 1982). In addition, it appears possible with the small lens distortion of modern lenses, that theoretical distortion and actual average radially symmetrical lens distortion for a certain lens type may be identical.

The acceptance of a standard reference lens distortion for each lens type, e.g. defined by a polynomial using manufacturer's data, would make it possible to use the same criterion for the selection of the calibrated focal length and to introduce the equivalent focal length. While the criterion for the selection of the calibrated focal length and the resulting positioning of the lens distortion curve is not a matter of importance, the introduction of the equivalent focal length is desirable when using stellar calibration procedures. Both focal lengths are determined for the mounted lens.

The location of the principal point of best symmetry is dependent upon the locations of the points used in its determination. Using only points "...along each diagonal of the image format..." may not do justice to calibration procedures providing a nearly uniform distribution of points throughout the format as do stellar calibration, artificial stellar calibration, and systems calibration over a test field. More work is needed to clarify the extent of possible differences before reformulating this section.

Since the selection of a principal point of best symmetry does not affect the tangential component of the lens distortion, which is in its size related to the symmetrical radial component, the elimination from a camera calibration report of the point of autocollimation and the lens distortion referenced to it, as recommended occasionally, cannot be supported by the authors.

The location of fiducial marks is reported by some camera calibration institutions in the form of distances between fiducial marks. The increasing use of comparators and analytical plotters makes it desirable to report the location of the fiducial marks, the principal points and the fiducial centre in the same image coordinate system. We believe that this system should be related to the film transport direction. This image coordinate system could also be used for the reporting of the lens distortion including the decentring distortion.

Summing up our comments on the definitions, we suggest replacing the theorectical distortion with lens distortion reference data, introduce the equivalent focal length and an image coordinate system, and select either the reference plane or image plane for use.

2.3 Focus Setting

Cameras shall normally be supplied for calibration and for use focussed to give best average photographic resolving power. A different focussing criterion may be used only if it is clearly justified by a user requirement and is stated in the report. Calibration shall be carried out in the actual focal plane of the camera, that is in the position the emulsion surface, if it were a true plane, would assume in service. If in any type of camera the intended shape of the emulsion surface is not a plane, the calibration shall be carried out in the intended surface, or by a method which produces equivalent results.

Discussion

The authors have no differences with the preceding statements.

2.4. Target

A high contrast target shall be used.

Discussion

Two types of targets need to be considered here, the targets for the determination of the lens distortion and the targets for the determination of focus setting and, at the same time, a check on the resolution of the lens. A test target is designated as high contrast when the ratio of the transmittances or reflectances between the light and dark areas is greater than 100 (a density difference greater than 2.0), and is designated medium contrast with a smaller ratio, typically about 10. If the target for the determination of the lens distortion is one of medium rather than high contrast, it is easier to guarantee that when the calibration plate is developed all collimator target images will be located on the straight-line section of the D-Log E curve when all collimator targets are illuminated identically.

The requirement of high contrast was originally intended for resolving-power targets used to check the focus and the stability of the resolving power of a lens. If the determination of lens distortion and the check on image quality are not combined in one operation, the definition of the target should be based on the requirements for the lens distortion determination.

Nothing is said about the shape of the target. Collimators are usually equipped with crosses as targets, and the photographic images of these crosses are measured with pairs of crosshairs. This is contrary to the photogrammetric practice where circular targets are predominantly used when high accuracy is to be achieved, and the images of these targets are measured using a dot as measuring mark. It is possible that differences in point loations may result from the two basically different targets when the image is produced by a non-symmetrical wave front. Investigations are needed to clarify this conern before the target shape is included in the "Recommended Procedures....".

2.5 Collimators

2.5.1 Each target shall be placed at the focus of a collimator. A single·collimator which is set at various angles relative to the cameras may be used, or an array of collimators providing all the necessary field angles. Collimator lenses shall be of sufficient quality and focal length shall be focused accurately enough that displacements of the camera lens which permit of it being entirely filled do not introduce significant errors in measurements.

NOTE: Spherical aberration of the collimator objectives or small focussing errors could introduce significant inaccuracies. Such effects should be checked carefully.

2.5.2 The collimator apertures and the positions of the collimators relative to the camera shall be such that the entrance pupil of the camera lens is filled with light from every part of the illuminted collimator field.

2.5.3 Luminance shall be uniform over the collimator field and of the spectral quality specified in section 1.4.

Discussion

The authors have no differences with the preceeding statements.

2.6 Number of Field Angles

Targets shall be photographed at the principal point of autocollimation and along at least the two diagonals of the image format. They shall be photographed at a sufficient number of off-axis angles (at least 6 on a semi-diagonal) in each half field to permit accurate plotting of the distortion to the limit of the field.

Discussion

The number and the location of the collimators may influence the result of a calibration and therefore contribute to differences between calibrations of the same lens at different institutions. The introduction of standard lens distortion reference curves for all lens types and the use of these curves by all institutions would reduce the task of determining lens distortion to a determination of the deviations from these curves. Hence, the number and locations of the collimators would no longer influence the result to the same extent; also, a calibration would be meaningful even if only very few collimators were available for the lens distortion determinations, as is the case for longer focal length lenses. For example, camera calibration at the National Research Council of Canada is carried out with collimators located at $\frac{45}{8} i^\circ$ with $i = 0$ to 10. For lenses with the focal lengths (f) = 86, 153, 210, 305 and 610 mm the number of available collimators at off-axis angles is, respectively, 10, 8, 6, 4 and 2.

The introduction of standard lens distortion curves defining lens distortion throughtout the useful image format would also reduce the potential problems resulting from the extrapolation of lens distortion values for radial distances larger than that of the last available collimator image. For the example of different focal lengths given in the preceding paragraph, extrapolation, for a useful image format of 225 mm by 225 mm with a semi-diagonal of 159 mm, would be necessary for radial distances exceeding approximately 129, 153, 140, 126 and 121 mm respectively. In an ideally flown photogrammetric block with 60% forward overlap and 20% sidelap, four of the nine essential image locations would be located at a radial distance of 130 mm and require lens distortion extrapolation for three of the five types of lenses.

2.7 Filters

Any filter normally used on the camera shall be in place during the test. If more than one filter may be used in service, the camera shall be tested with each. Any filter used on the camera during tests shall be fully identified in the report. If its orientation on the camera is not well established by marks or indexing devices it shall be recorded in the report.

Discussion

A microdensitometer trace should be made and recorded of the antivignetting coating located on the lens side of the camera's filter. A copy of this trace (a sample is given in Fig. 1) should accompany the camera calibration report to determine if any deterioration has occured to the antivignetting coating since the last calibration.

The deterioration of these coatings due to normal cleaning changes the relative illumination or light falloff in the image plane from the axis to the edges of the format area. It is not unusual to find the coating deteriorated or completely removed after a few years of service.

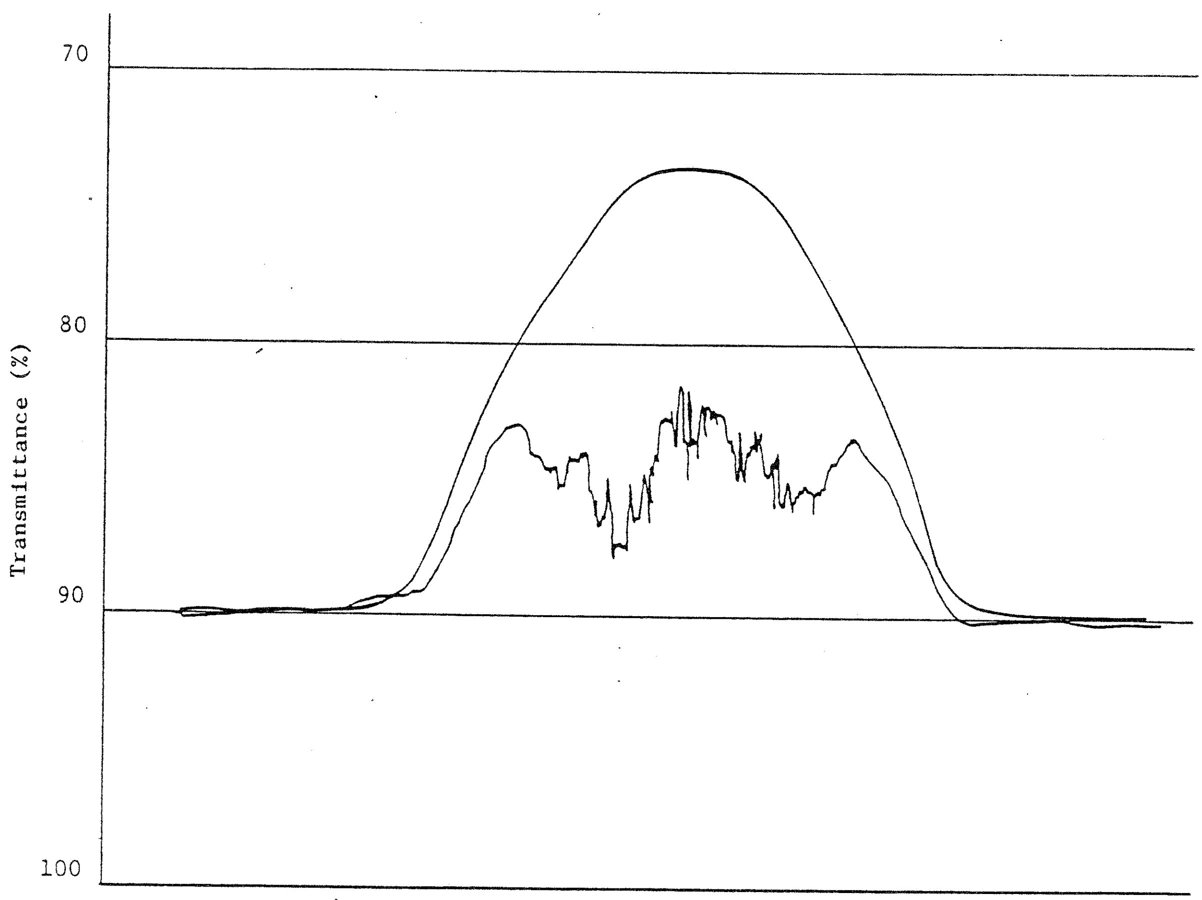

Figure 1. Microdensitometer trace of the antivignetting coating on a camera's filter. Lower trace shows deterioration from normal service, upper trace is designed density gradient.

2.8 Apertures

Tests shall be made at full aperture and at any other apertures for which data are desired. The apertures used shall be specified in the report. For full characterization of a type of camera tests shall be made at three or more apertures, except where the camera mechanism provides fewer than three apertures.

Discussion

The authors have no differences with the preceeding statement.

2.9 Negative Material

2.9.1 The emulsion used should preferably be the same as is used in service. However, an emulsion of similar spectral sensitivity and gamma but with different grain characteristics is acceptable, or any emulsion which gives equivalent results.

2.9.2 For cameras in which the intended shape of the emulsion surface is a plane, the emulsion shall be supported on a glass plate. Flatness of the plate at the time of exposure shall at least meet the tolerance for the flatness of the film plane in the camera under test. Perferably it should meet one-tenth of this tolerance. Alternatively the plate should be adquately stable, its unflatness should be measured and computational corrections applied.

NOTE: For present (1960) accurate calibration it is desirable that the plate be flat, or its errors known, to ± 1 micron (see section 2.13.2).

2.9.3 For cameras in which the intended shape of the emulsion surface is not a plane, a plate of the intended shape shall be used, or a flat plate may be used and corrections applied if it is established that the corrections lead to results equivalent to measurements made in the intended surface.

Discussion

In the discussion to section 2.1 we have already pointed out the desirability of also checking the operation of the entire camera system, including the magazine, by taking exposures of the collimator images on film. The film used should be the same kind as that used with the camera in photographic missions. For evaluation, contact diapositives on (miroflat) glassplates should be used.

If the operation of the magazine were to be tested in operational conditions by a suitable procedure excluding the lens cone, the same kind of film as used with the camera for photographic missions should also be used.

2.10 Exposure

The exposure level shall correspond sufficiently closely to that used in practice to ensure that no signficant errors in image position are introduced.

NOTE: When the energy distribution in the spatial image is not symmetrical, the apparent centre of gravity of the photographic image may be displaced by underexposure or by overexposure.

Discussion

It is important to image on the straight-line section of the D-Log E curve, as already pointed out in the discussion to section 2.4.

2.11 Processing

Processing of the service emulsion shall be equivalent to that used in practice. An alternative emulsion permitted under section 2.9.1 shall be processed to give the equivalent results required there. Care should be taken to avoid conditions which would produce strains in the emulsion.

Discussion

The authors have no differences with the preceeding statement.

2.12 Measurements

Measurements shall be made in a way which permits all tangential measured distortions to be based on a single reference system.

Discussion

The measurements should be carried out in such a way that the overall lens distortion could be determined and reported in tabular form as corrections to x- and y-coordinate readings.

2.13 Shape and Locating Surfaces for Films and Plates

2.13.1 The departure of the film or plate locating surfaces from flatness, or from some other intended shape, shall be determined.

2.13.2 These departures shall be computed with reference to an ideal plane (or other intended surface) so positioned as to fit the real surface well and to make the maximum value of absolute departure as small as possible by making the numerically largest positive and negative departures equal in absolute value. The positive direction shall be away from the lens.

2.13.3 When a locating surface is in the magazine, all magazines to be used with the camera shall be tested.

Discussion

In the discussion to section 2.2 (Definitions) the distinction between reference plane and image plane was introduced. This distinction proves also useful when considering cameras where the film locating surface is by design not a plane. Here the reference plane would be that plane containing the reference marks, for example the fiducial marks, while the image "plane" would be the surface of the film when brought into position for exposure. Laboratory calibration of the only camera type still in use which has a non-flat film locating surface, is routinely carried out using a microflat glass plate for the determination of the lens distortion only. The radial image displacement caused by the non-flat film locating surface are then added to the lens distortion. The use of film and the magazine would result in the determination of the sum of lens distortion and radial displacements.

As stated earlier, the use of film to make test exposures with the camera's magazine provides a direct laboratory simulation of the camera/magazine performance. Because of small defects in the film locating surface for any camera, such as variation from the intended shape of the film platen, irregularity of the film flattening system (vacuum) and variations of the focal plane frame, all magazines intended for use with a camera should be used to make film test exposures (Meier 1972). From these film exposures, contact diapositives that are measured for the calibration of the complete camera system are printed. Each film magazine would have an individual calibration report.

Tables I to VI show the results of three different calibrations of the same lens/camera system, first with flash plates (Tables I and II), then using two different film magazines. To show the degree of precision for the determination of the lens distortion of the lens/camera system, five different sets of film exposure/glass diapositives were measured for three camera systems. Each set is the average of a pair of similar exposures. The camera's film magazine was used to make test exposures of the collimator banks, and from these exposures contact glass diapositives were made for comparator measurements. The results are reported in Tables VII to IX. As in Tables I through VI, the preliminary steps in the measurements are not described. The final values of the distortion along each of four semi-diagonals and the averages of these four sets of values with the calibrated focal length are given. In no case did a semidiagonal value depart from the five-set average value by more than 2 micrometers.

Since December 1, 1977, the U.S. Geological Survey has required that all magazine platens be equipped with an identification marker that will register a number on each frame of the original film at the time of exposure. The recording of the platen number ensures positive identification of the film magazine used. When an organization has more than one camera of the same manufacture, magazines can be interchanged inadvertently.

2.14 Presentation of Results

2.14.1 The report should give at least the following data:

2.14.2 The location of the principal point of autocollimation with respect to the fiducial centre.*

2.14.3 Calibrated principal distance, or calibrated focal length with criterion used to establish it.

2.14.4 Curves (with plotting points shown) or a table of radial measured distortion, having as its origin the principal point of autocollimation as defined in section 2.2.3, along each of the four semi-diagonals and of the average of these four sets of values.*

2.14.5 A statement of the maximum difference between radial measured distortion at any field angle.*

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* If radial distortion relative to the principal point of best symmetry is also reported it should be clearly named and the position of the principal point of best symmetry should be given with respect to the fiducial center.

TABLE I

Values of radial lens distortion (in mm) measured from flash plates exposed on a camera focal plane. The distortion is measured for each of the four radii of the plane separated by 90° in azimuth. Azimuth angles (0 A-C), (90 A-D), etc. are located on the reference plane diagonals between the letter-indicated fiducial marks (A to D in Figures 2 to 5) respectively.

FIELD ANGLE	AVERAGE DISTORTION	AZIMUTH ANGLES			
		0 A-C	90 A-D	180 B-D	270 B-C
7.50	-0.002	0.000	-0.002	-0.002	-0.003
15.00	-0.004	-0.003	-0.004	-0.004	-0.004
22.75	-0.004	-0.002	-0.004	-0.005	-0.004
30.00	0.001	0.002	0.000	0.002	0.001
35.00	0.005	0.007	0.002	0.005	0.004
40.00	-0.001	0.000	-0.002	0.002	-0.004

CALIBRATED FOCAL LENGTH 153.350 mm

TABLE II

Mean lens distortion correction values (in µm) at 1 mm intervals, and computer generated distortion curve for the camera described in Table I.

THE MEAN RADIAL DISTORTION CORRECTION VALUES AT 1 MM. INTERVALS

FROM	TO										
1	10	0.	0.	1.	1.	1.	1.	2.	2.	2.	2.
11	20	3.	3.	3.	3.	3.	3.	3.	3.	4.	4.
21	30	4.	4.	4.	4.	4.	4.	4.	4.	4.	4.
31	40	4.	4.	4.	4.	4.	4.	4.	4.	4.	4.
41	50	4.	4.	4.	4.	3.	3.	3.	3.	3.	3.
51	60	3.	3.	3.	3.	2.	2.	2.	2.	2.	2.
61	70	2.	2.	1.	1.	1.	1.	1.	1.	1.	1.
71	80	0.	0.	0.	0.	-0.	-0.	-0.	-0.	-1.	-1.
81	90	-1.	-1.	-1.	-1.	-1.	-1.	-1.	-1.	-2.	-2.
91	100	-2.	-2.	-2.	-2.	-2.	-2.	-2.	-2.	-2.	-2.
101	110	-2.	-2.	-2.	-2.	-2.	-2.	-2.	-2.	-2.	-2.
111	120	-2.	-2.	-2.	-2.	-2.	-2.	-2.	-2.	-2.	-2.
121	130	-1.	-1.	-1.	-1.	-1.	-1.	-0.	-0.	0.	0.
131	140	1.	1.	1.	1.	2.	2.	2.	2.	3.	3.
141	150	3.	4.	4.	4.	5.	5.	5.	6.	6.	7.

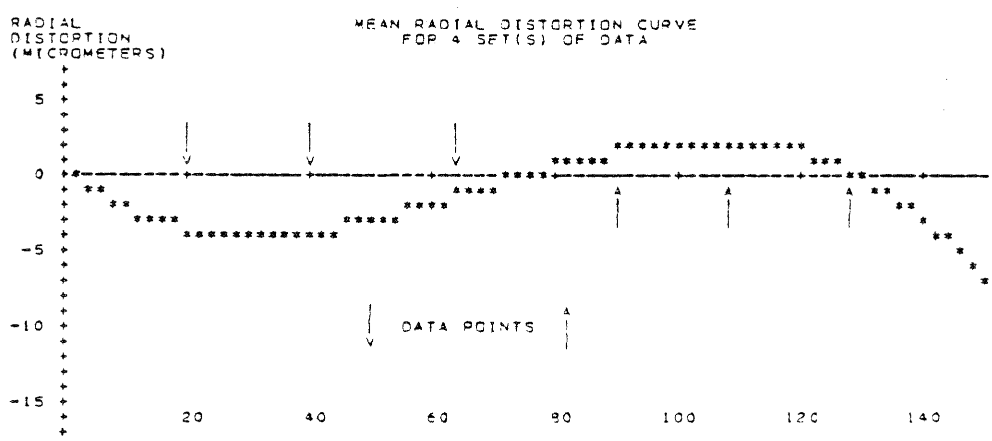

TABLE III

Values of radial lens distortion (in mm) for the same lens-camera unit described in Table I and II except the camera's first film magazine was used to make test exposures of the collimator banks, and from these exposures contact glass diapositives were made for the evaluation of distortion and calibrated focal length.

FIELD ANGLE	AVERAGE DISTORTION	AZIMUTH ANGLES			
		0 A-C	90 A-D	180 B-D	270 B-C
7.50	-0.003	-0.002	-0.001	-0.003	-0.006
15.00	-0.004	-0.001	-0.007	-0.001	-0.004
22.75	-0.003	-0.001	-0.004	-0.002	-0.006
30.00	0.002	0.004	-0.003	0.003	-0.001
35.00	0.004	0.009	0.002	0.005	0.001
40.00	-0.005	-0.004	-0.008	0.002	-0.005

CALIBRATED FOCAL LENGTH 153.371 mm

TABLE IV

Mean lens distortion correction values (in μm) at 1 mm intervals, and computer generated distortion curve for the camera described in Table III.

THE MEAN RADIAL DISTORTION CORRECTION VALUES AT 1 MM. INTERVALS

FROM	TO										
1	10	0.	0.	1.	1.	2.	2.	2.	2.	3.	3.
11	20	3.	3.	4.	4.	4.	4.	4.	4.	5.	5.
21	30	5.	5.	5.	5.	5.	5.	5.	5.	5.	5.
31	40	5.	5.	5.	5.	5.	5.	5.	5.	5.	5.
41	50	4.	4.	4.	4.	4.	4.	4.	4.	3.	3.
51	60	3.	3.	3.	3.	2.	2.	2.	2.	2.	2.
61	70	2.	2.	1.	1.	1.	1.	0.	0.	0.	0.
71	80	-0.	-0.	-0.	-0.	-1.	-1.	-1.	-1.	-1.	-1.
81	90	-2.	-2.	-2.	-2.	-2.	-2.	-2.	-2.	-2.	-2.
91	100	-2.	-2.	-2.	-2.	-3.	-3.	-3.	-3.	-3.	-3.
101	110	-2.	-2.	-2.	-2.	-2.	-2.	-2.	-2.	-2.	-2.
111	120	-1.	-1.	-1.	-1.	-1.	-1.	-0.	0.	0.	1.
121	130	1.	1.	2.	2.	2.	3.	3.	3.	4.	4.
131	140	5.	5.	6.	6.	7.	8.	8.	9.	9.	10.
141	150	11.	12.	12.	13.	14.	15.	15.	16.	17.	18.

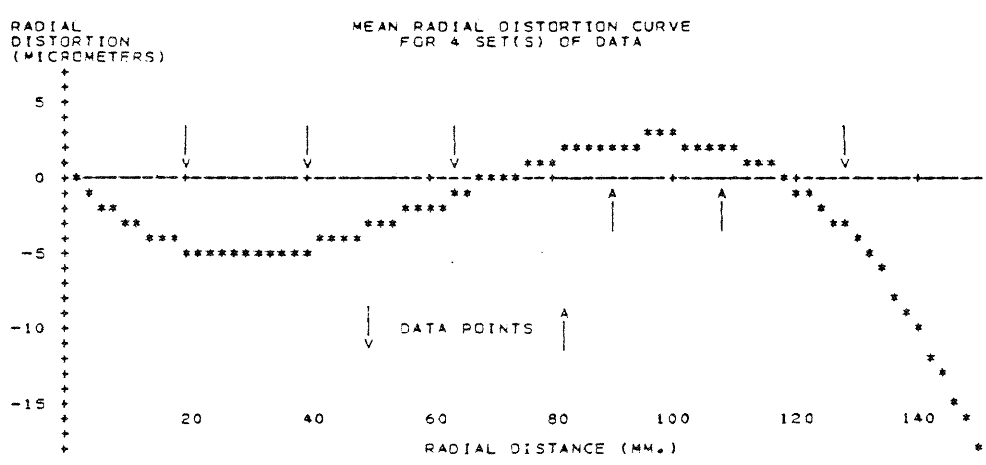

TABLE V

Values of radial lens distortion (in mm) for the same lens-camera unit described in Tables I through IV except the camera's second film magazine was used to make test exposures of the collimator banks, and from these exposures contact glass diapositives were made for the evaluation of distortion and calibrated focal length.

FIELD ANGLE	AVERAGE DISTORTION	AZIMUTH ANGLES			
		0 A-C	90 A-D	180 B-D	270 B-C
7.50	-0.002	-0.003	-0.002	-0.001	-0.001
15.00	-0.003	-0.003	-0.004	-0.001	0.000
22.75	-0.002	-0.001	-0.001	-0.003	-0.002
30.00	0.001	0.002	0.004	0.001	0.002
35.00	0.002	0.004	0.002	0.003	0.001
40.00	-0.005	-0.010	-0.004	-0.008	-0.001

CALIBRATED FOCAL LENGTH 153.374 mm

TABLE VI

Mean lens distortion correction values (in µm) at 1 mm intervals, and computer generated distortion curve for the camera described in Table V.

THE MEAN RADIAL DISTORTION CORRECTION VALUES AT 1 MM. INTERVALS

FROM	TO										
1	10	0.	0.	1.	1.	1.	1.	2.	2.	2.	2.
11	20	2.	2.	3.	3.	3.	3.	3.	3.	3.	3.
21	30	3.	3.	3.	3.	3.	3.	3.	3.	3.	3.
31	40	3.	3.	3.	3.	3.	3.	3.	3.	3.	3.
41	50	3.	3.	3.	3.	3.	3.	2.	2.	2.	2.
51	60	2.	2.	2.	2.	2.	2.	1.	1.	1.	1.
61	70	1.	1.	1.	1.	0.	0.	0.	0.	0.	-0.
71	80	-0.	-0.	-0.	-0.	-1.	-1.	-1.	-1.	-1.	-1.
81	90	-1.	-1.	-1.	-1.	-1.	-1.	-1.	-1.	-1.	-1.
91	100	-1.	-1.	-2.	-2.	-2.	-2.	-2.	-2.	-1.	-1.
101	110	-1.	-1.	-1.	-1.	-1.	-1.	-1.	-1.	-1.	-1.
111	120	-0.	-0.	-0.	0.	0.	0.	1.	1.	1.	1.
121	130	2.	2.	2.	2.	3.	3.	3.	3.	4.	4.
131	140	4.	5.	5.	5.	6.	6.	7.	7.	8.	8.
141	150	9.	9.	10.	10.	11.	12.	12.	13.	13.	14.

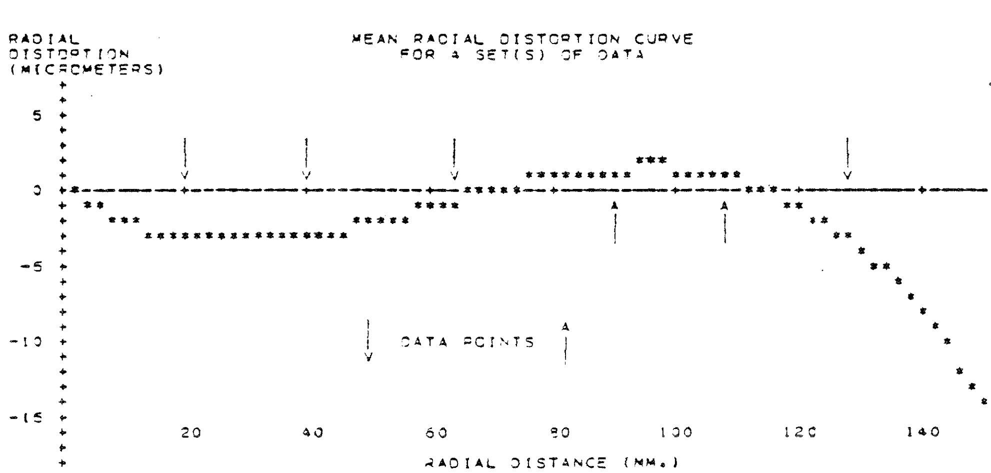

TABLE VII. Radial distortion in micrometers for five sets of glass diapositives contact printed from film exposures of the collimator banks. Wild RC10 #1768, UAg/4 #13025

Set 1:

Field Angle	Average	Azimuth Angle 0°	90°	180°	270°
7.5°	3	3	2	4	3
15°	3	4	2	0	5
22.5°	2	-1	3	1	4
30°	3	-1	5	2	4
35°	1	1	4	-2	3
40°	-5	-7	-4	-6	-3

Set 2:

Field Angle	Average	Azimuth Angle 0°	90°	180°	270°
7.5°	3	3	2	3	4
15°	3	4	3	0	5
22.5°	2	-2	4	1	4
30°	3	1	3	3	6
35°	1	1	2	-2	2
40°	-5	-6	-4	-5	-6

Set 3:

Field Angle	Average	Azimuth Angle 0°	90°	180°	270°
7.5°	2	3	1	2	3
15°	3	3	2	-1	7
22.5°	2	-2	5	0	4
30°	3	-1	6	2	5
35°	1	0	3	-3	4
40°	-5	-6	-4	-5	-5

Set 4:

Field Angle	Average	Azimuth Angle 0°	90°	180°	270°
7.5°	3	2	2	5	2
15°	3	1	4	2	3
22.5°	1	0	4	-1	3
30°	2	0	3	2	4
35°	1	-2	1	0	3
40°	-4	-3	-3	-6	-5

Set 5:

Field Angle	Average	Azimuth Angle 0°	90°	180°	270°
7.5°	2	2	1	2	3
15°	3	4	3	0	6
22.5°	1	-1	5	-1	3
30°	3	-1	5	2	4
35°	1	-2	3	-1	4
40°	-5	-5	-4	-6	-4

Average of five sets:

Field Angle	Average	Azimuth Angle 0°	90°	180°	270°
7.5°	3	3	2	3	3
15°	3	3	3	0	5
22.5°	2	-1	4	0	4
30°	3	0	4	2	5
35°	1	0	3	-2	3
40°	-5	-5	-4	-6	-5

Calibrated Focal Length:

Set 1:	153.086 mm
Set 2:	153.086 mm
Set 3:	153.086 mm
Set 4:	153.085 mm
Set 5:	153.085 mm
Avg. :	153.086 mm

TABLE VIII. Radial distortion in micrometers for five sets of glass diapositives contact printed from film exposures of the collimator banks. Wild RC10 #1945, UAg I #6020

Set 1:

Field Angle	Average	Azimuth Angle 0°	90°	180°	270°
7.5°	-1	-2	0	0	-2
15°	-3	-1	-4	-5	-4
22.5°	0	-2	2	-2	2
30°	7	3	9	4	10
35°	3	2	7	-2	6
40°	-6	-11	-2	-8	-2

Set 2:

Field Angle	Average	Azimuth Angle 0°	90°	180°	270°
7.5°	-1	-2	-3	0	-1
15°	-4	-2	-5	-4	-3
22.5°	-1	-3	0	-1	2
30°	6	3	7	5	8
35°	3	4	5	-1	6
40°	-5	-10	-1	-8	-3

Set 3:

Field Angle	Average	Azimuth Angle 0°	90°	180°	270°
7.5°	-1	-1	-2	-1	-1
15°	-4	-2	-4	-6	-4
22.5°	-1	-3	0	-2	1
30°	6	2	7	4	9
35°	3	2	6	-2	7
40°	-4	-9	0	-7	-2

Set 4:

Field Angle	Average	Azimuth Angle 0°	90°	180°	270°
7.5°	-1	-2	-2	1	0
15°	-3	-3	-2	-4	-4
22.5°	-1	-5	0	-2	2
30°	6	4	8	4	9
35°	4	3	6	-2	7
40°	-5	-9	-1	-7	-3

Set 5:

Field Angle	Average	Azimuth Angle 0°	90°	180°	270°
7.5°	-1	0	-3	1	-1
15°	-3	-1	-3	-6	-3
22.5°	0	-3	1	0	1
30°	6	4	7	4	9
35°	3	2	6	-3	7
40°	-5	-10	-1	-6	-4

Average of five sets:

Field Angle	Average	Azimuth Angle 0°	90°	180°	270°
7.5°	-1	-1	-2	0	-1
15°	-3	-2	-4	-5	-4
22.5°	-1	-3	1	-1	2
30°	6	3	8	4	9
35°	3	3	6	-2	7
40°	-5	-10	-1	-7	-3

Calibrated Focal Length:

Set 1:	152.882 mm
Set 2:	152.882 mm
Set 3:	152.882 mm
Set 4:	152.882 mm
Set 5:	152.882 mm
Avg. :	152.882 mm

TABLE IX. Radial distortion in micrometers for five sets of glass diapositives contact printed from film exposures of the collimator banks. Wild RC8 #826, UAg #356, Mag. #958

Set 1:

Field Angle	Average	Azimuth Angle 0°	90°	180°	270°
7.5°	6	4	5	7	7
15°	8	9	8	8	9
22.5°	6	5	9	4	5
30°	2	0	4	1	3
35°	-3	-4	-3	-5	0
40°	-5	-4	-6	-4	-7

Set 2:

Field Angle	Average	Azimuth Angle 0°	90°	180°	270°
7.5°	6	6	6	5	6
15°	8	8	10	6	10
22.5°	5	3	8	4	5
30°	2	-1	5	1	3
35°	-3	-4	-2	-6	-1
40°	-5	-4	-7	-3	-5

Set 3:

Field Angle	Average	Azimuth Angle 0°	90°	180°	270°
7.5°	5	3	5	6	7
15°	8	9	10	6	9
22.5°	6	4	9	6	7
30°	3	1	6	2	4
35°	-3	-4	-3	-5	-1
40°	-6	-6	-6	-5	-6

Set 4:

Field Angle	Average	Azimuth Angle 0°	90°	180°	270°
7.5°	6	4	6	6	6
15°	9	10	10	7	9
22.5°	6	4	9	6	7
30°	2	0	4	2	4
35°	-3	-3	-3	-6	-1
40°	-6	-6	-6	-5	-7

Set 5:

Field Angle	Average	Azimuth Angle 0°	90°	180°	270°
7.5°	6	5	6	5	6
15°	9	9	10	7	9
22.5°	6	4	9	5	7
30°	2	-1	4	2	3
35°	-3	-6	-1	-6	-1
40°	-6	-4	-7	-5	-7

Average of five sets:

Field Angle	Average	Azimuth Angle 0°	90°	180°	270°
7.5°	6	4	6	6	6
15°	8	9	10	7	9
22.5°	6	4	9	5	6
30°	2	0	5	2	3
35°	-3	-4	-2	-6	0
40°	-6	-5	-6	-4	-6

Calibrated Focal Length:

Set 1:	152.477 mm
Set 2:	152.477 mm
Set 3:	152.478 mm
Set 4:	152.478 mm
Set 5:	152.477 mm
Avg. :	152.477 mm

2.14.6 A statement of the maximum value of tangential measured distortion based on the reference frame which makes this a minimum by making maximum values of opposite sign equal in magnitude.

2.14.7 Distances between opposite pairs of fiducial marks, and the angle between the fiducial axes. The precise points involved should be thoroughly identified.

2.14.8 The maximum departures ($\pm$) of the film locating surfaces from their correct shapes, or more complete information if required.

2.14.9 If requested, a table giving the radial and tangential measured distortion at each point measured, and/or a statement of the orientation of the line through the principal point along which tangential measured distortion is calculated to be a maximum.

2.14.10 A Statement of the accuracies of all the information provided.

Discussion

At the present time, all camera calibration facilities report principal point and fiducial centre location in a coordinate system, and some do so for the location of the fiducial marks. The methods used are all similar, with the exception of fiducial mark identification and coordinate origin. Fiducial centre, principal point of best symmetry and principal point of autocollimation are used as the origin. The coordinates routinely reported are:

- Fiducial centre derived from corner fiducial marks
- Fiducial centre derived from midside fiducial marks
- Principal point of autocollimation
- Principal point of best symmetry

There are many different coordinate systems in use today by various camera calibration laboratories and camera manufacturers (Ziemann 1978a,b). Because of the different methods, the format area on which results were based, and the diversity of reporting calibration results, it is impossible to unambiguously interpret or arrive at true comparisons. The reports of the U.S. Geological Survey and the National Research Council of Canada may serve here as two examples. At the USGS, the standard practice is the use of the principal point of autocollimation as the origin in camera calibration reports and in computational programs for analytical photogrammetry. For USGS calibration reports, the camera data strip area is used as the standard reference on which the eight-fiducial coordinate system is based. At NRC, the principal point of autocollimation and the principal point of best symmetry are reported as coordinate differences with reference to the fiducial centre (only four fiducial marks are required in Canada), while the location of the fiducial marks is given by the distances between opposite pairs of fiducial marks. A change in the reporting of these locations and of the locations of the two principal points and the fiducial centre is planned; all points will be reported in a coordinate system with the fiducial centre as origin. The x-axis will point to the following photograph disregarding the location of the data strip. Figures 2 through 7 show the orientation of the image coordinate system adopted by the U.S. Geological Survey for four different types of cameras in general use today; the coordinate system used at NRC for RC10 cameras (Fig. 4) is rotated by 180°. These cameras could be equipped with four or eight fiducial marks. The Zeiss-Jena MRB cameras have glass scales with crosses at 10 mm intervals

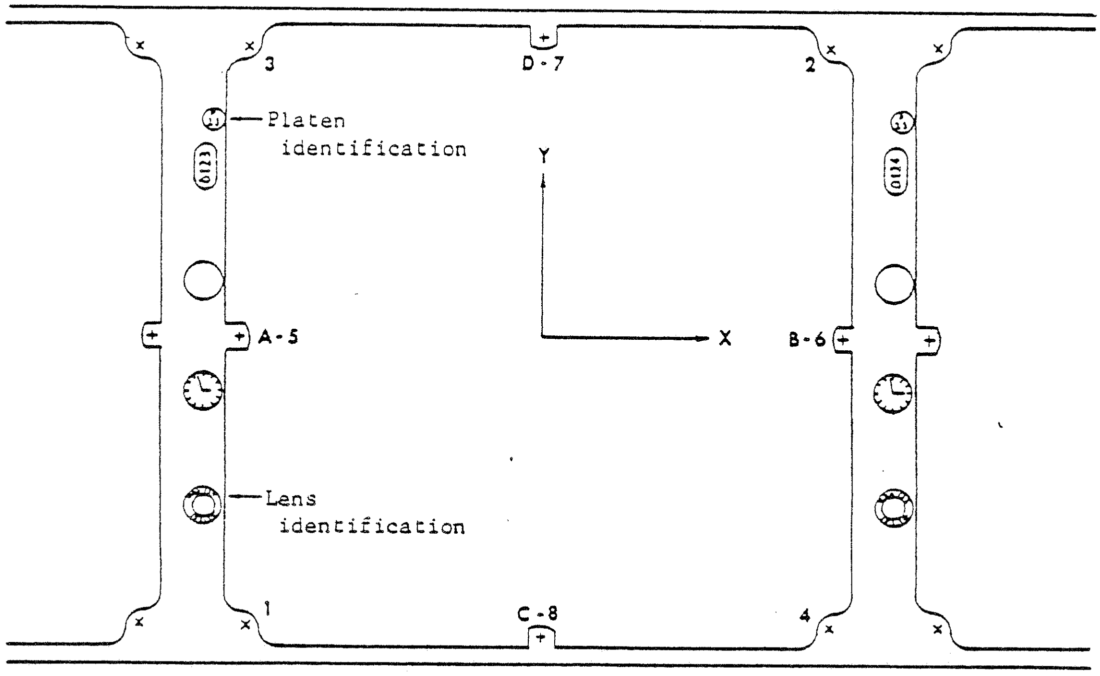

Fig. 2. Wild Heerbrugg RC8 Camera.

The camera is viewed from the back, or a contact positive viewed with the emulsion up. The data strip is to the left. The platen identification marker is in the upper left corner. For this orientation the film transport is from right to left. There is no asymmetrically located obstruction inside the frame area for this camera, however the midside fiducials have independent features that allow for partial orientation identification.

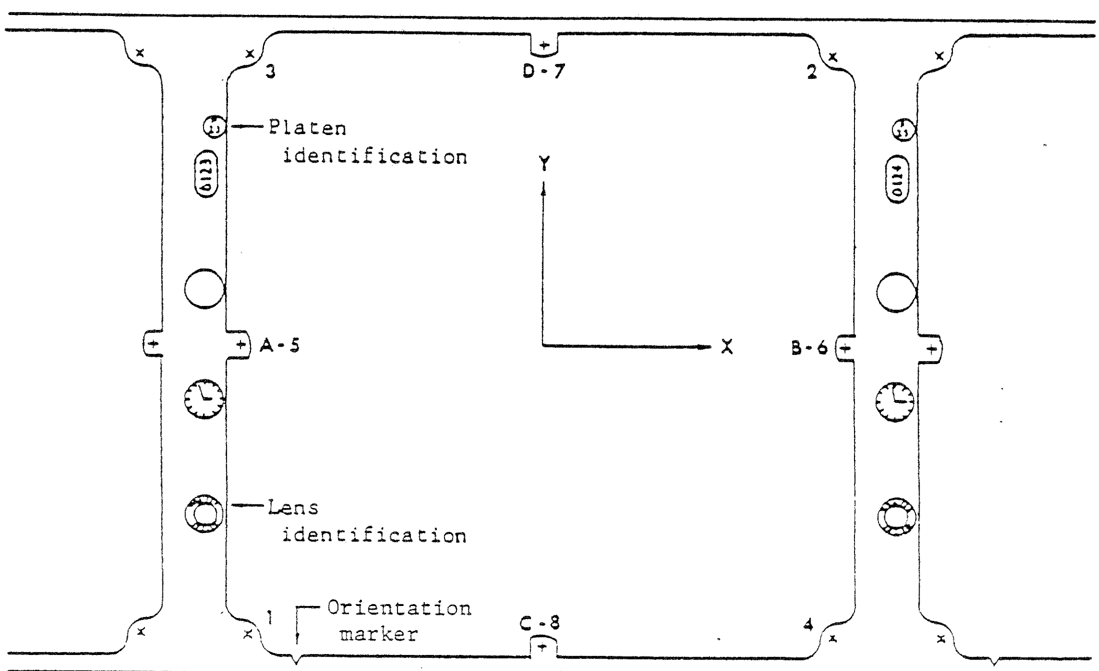

Fig. 3. Wild Heerbrugg RC8 Camera.

The camera is viewed from the back, or a contact positive viewed with the emulsion up. The data strip is to the left. The platen identification marker is in the upper left corner. For this orientation the film transport is from right to left. There is no asymmetrically located obstruction inside the frame area for this camera. To provide positive identification, a "V" notch "Orientation marker" has been filed in the focal frame as shown.

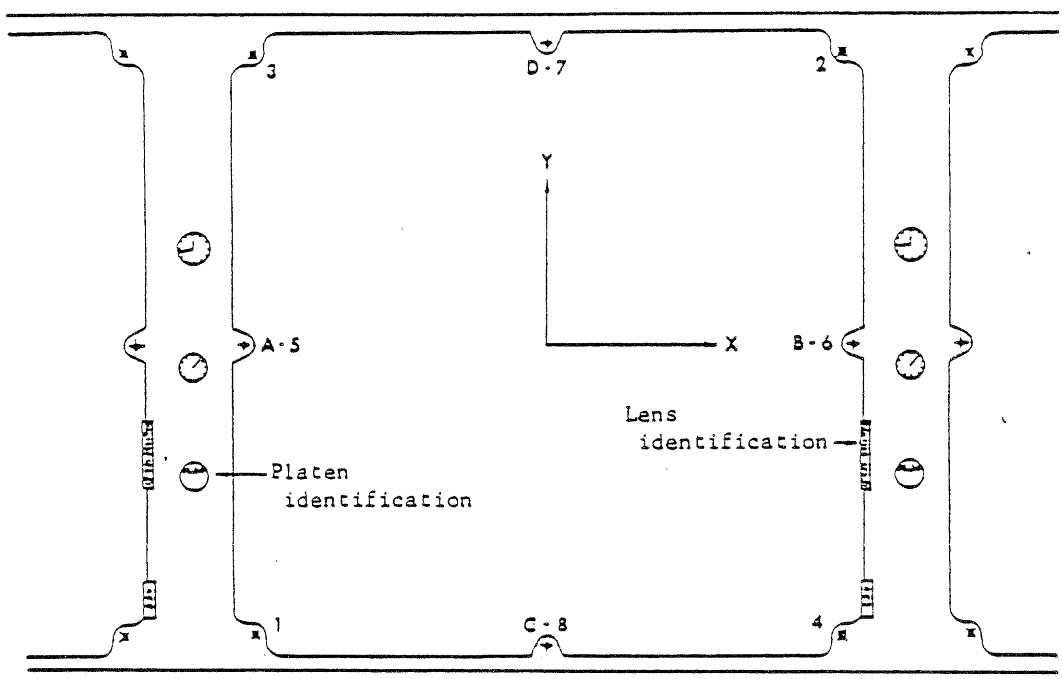

Fig. 4. Wild Heerbrugg RC10 Camera.

The camera is viewed from the back, or a contact positive viewed with the emulsion up. The data strip is to the left, with the platen identification located on the camera drive unit data card. The film platen is an intregal part of the camera drive unit. For this orientation the film transport is from left to right. The lens identification panel and the frame sequence number panel are used for positive orientation identification.

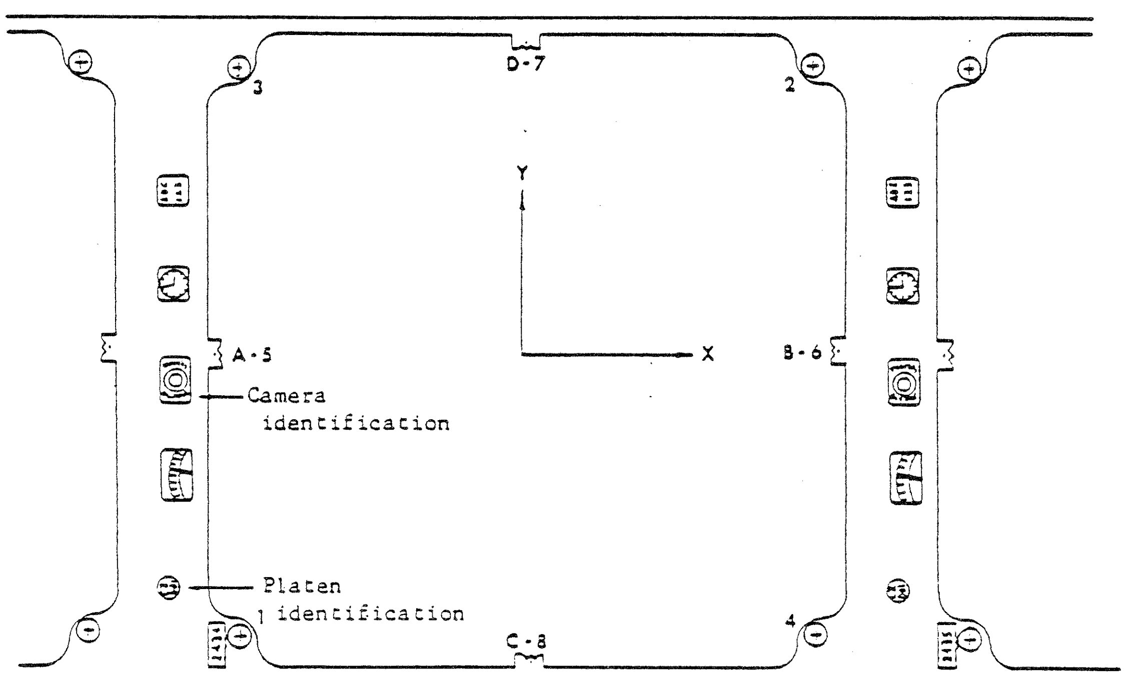

Fig. 5. Carl Zeiss Oberkochen RMK /23 Camera.

The camera is viewed from the back, or a contact positive viewed with the emulsion up. The data strip is to the left wth the platen identification located in the lower left corner. For this orientation the film transport is from right to left. The frame sequence number panel located in one corner of the format allows for positive orientation identification.

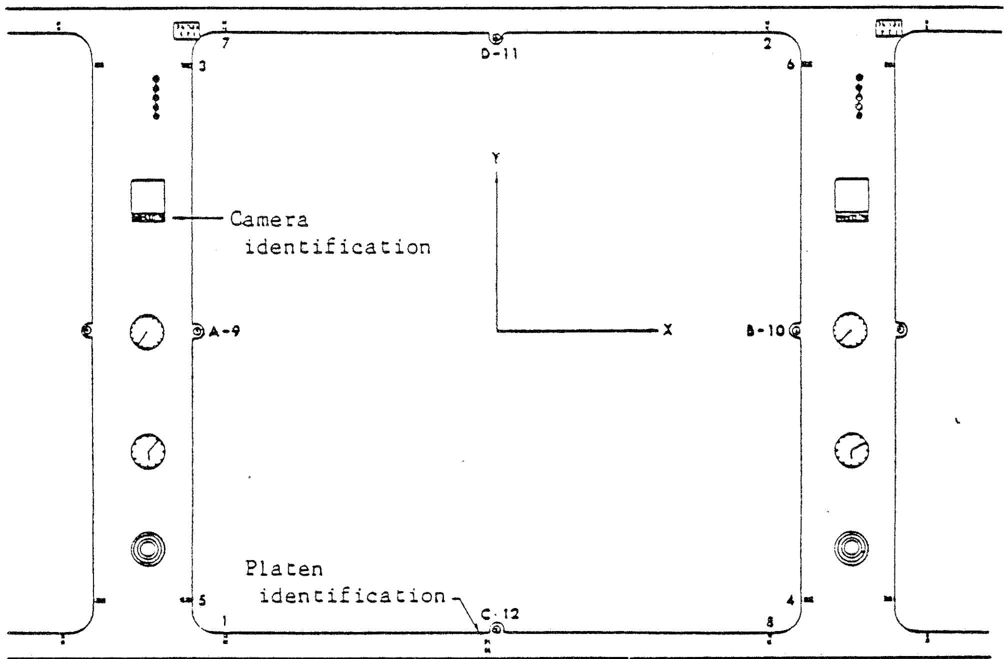

Fig. 6. Zeiss Jena MRB /2323 Camera.

The camera is viewed from the back, or a contact positive viewed with the emulsion up. The data strip is to the left with the platen identification located near the bottom midside fiducial. For this orientation the film transport is from right to left. The frame sequence number and calibrated focal length panel located in one corner of the format allows for positive orientation identification. In the interest of simplicity only the end crosses are shown of the format glass scales.

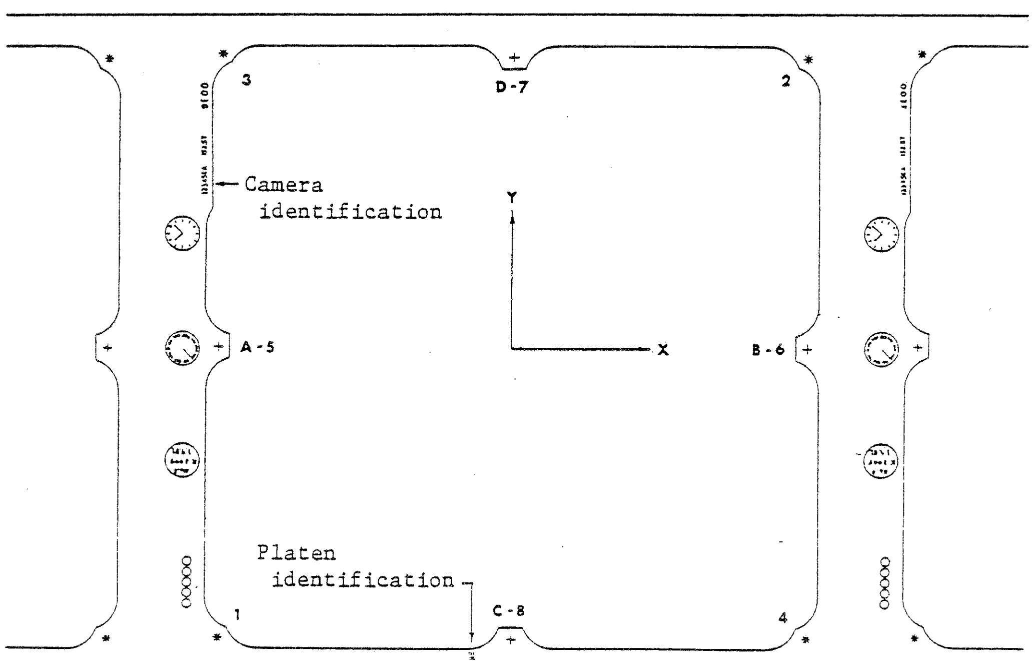

Fig. 7. Zeiss Jena LMK /2323 Camera.

The camera is viewed from the back, or a contact positive viewed with the emulsion up. The data strip is to the left with the platen identification located near the bottom midside fiducial. For this orientation the film transport is from right to left. The camera identification panel with the calibrated focal length and frame sequence number are used for positive frame orientation.

located along the four sides of the format (external reseau). The end marks of these scales can serve in place of the regular corner fiducial marks.

The determination of the lens distortion for the four semi-diagonals must be considered as a minimum; certain calibration procedures will provide the determination in additional radii, for example, the USGS procedure. Other procedures will result in a distribution of data points throughout the format which are not located on a limited number of radii. Since numerical photogrammetric procedures require the determination of the overall lens distortion - not only of the radial component - data points for the determination of the lens distortion should be distributed such that the lens distortion can be derived for the entire format area without extensive interpolation.

SUMMARY AND CONCLUSIONS

Section 2 (Calibration) of the document "Recommended Procedures for Calibrating Photogrammetric Cameras and Related Optical Tests" has been reviewed and suggestions for changes have been made. The discussion of the various subsections is based on experiences of the authors with their respective camera calibration facilities and procedures, and during their collaboration in the former Working Group on Image Geometry of Commission I of the International Society for Photogrammetry and Remote Sensing.

The present paper is a basis for discussion of the present section 2 and of changes which appear necessary to update the section in order that it may reflect present procedures and requirements. However, the changed section should be general enough to serve as a guide to all institutions carrying out camera calibrations without constraining their choice of methods. It is for this reason, that we have chosen to present differing views in some instances. Our main aim is a standardization in the reporting of camera calibrations to an extent which will make possible a direct comparison of results achieved with different procedures.

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