Calibration of Photogrammetric Lenses and Cameras at the National Bureau of Standards

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ABSTRACT: *A summary of calibrations performed at the National Bureau of Standards on lenses and cameras that are used in precise photogrammetric work is given. Brief description of the photographic and visual calibrations most frequently required are given. This paper includes a list of publications by members of the NBS staff that pertain to problems of lens and camera calibration.*

1.0 INTRODUCTION

THE success of a given mapping program depends in large measure upon the quality of the lenses used in the various operations intervening between the initial photography from the air and the production of a usable map. This was early recognized and various tests were developed to measure the optical constants and imaging properties of lenses. Emphasis was placed initially upon the characteristics of the lens in the aerial camera and many types of tests and calibrations were developed which proved useful. Subsequently, the performance of lenses used in other phases of the operation was investigated in greater detail with the aim of achieving the minimum loss in information content of the original photography.

A great deal of the early work in the measurement of lens performance was done at the National Bureau of Standards at the request of various mapping agencies. In the process of making these tests, information was gathered which when correlated with the quantitative and qualitative properties of the aerial photograph formed the basis for numerous lens and camera specifications.

At present, lenses that are to be used in the government mapping projects are required to satisfy minimum standards of performance as determined by the National Bureau of Standards or an accredited testing agency.

The present article presents a brief description of a number of the more commonly required calibrations together with definitions of the quantities measured.

2.0 CALIBRATION OF AERIAL CAMERA LENSES

The nature of the calibration of a given lens is determined by the requirements of the user. For some lenses, an accurate determination of the equivalent focal-length suffices. For lenses used in precision mapping cameras, accurate information on all the metrical properties of the lens that have a bearing upon the accuracy of the first map is required. These requirements are contained in specifications that list the specific requirements and set limits on the range in magnitude of the various quantities to be measured that will be acceptable for the given use.

2.1 CALIBRATIONS USING PHOTOGRAPHIC METHODS

It is customary to perform the calibrations on most lenses that are to be used in aerial photography by photographic methods. For this work the Bureau employs the precision lens testing camera (1) and the camera calibrator (31).

2.1.1 *Calibrations on lenses not mounted in cameras*

The lens-testing camera is used primarily for determination of such quantities as equivalent focal-length, *EFL*; back focal-distance, *BF;* distortion, *D;* and resolving-power, *RP*. This instrument consists of 10 collimators, spaced at 5° intervals which provide infinitely distant objects within the confines of the laboratory. Each collimator is equipped with a resolution chart in addition to the cross-lines in the reticle that are used in the precise determination of the angle separating the collimators. With this instrument, the entire region of usable imagery of the lens under test is sampled at intervals photographically to determine the plane of best average definition. When this plane has been located by examination of the imagery which is recorded on the test negative, the distance r_β separating the image at known angle β from the axial image is measured. The value of EFL is then obtained using the relation

$$EFL = r_\beta \cot \beta \quad (1)$$

The distance separating the rear vertex of the lens from the position occupied by the emulsion surface of the photographic plate when in the plane of best average definition is measured with the aid of a viewing microscope and a standard scale mounted on the bench ways; this is the back focal-distance, BF.

The measured value of BF is of prime interest to the camera maker in that it permits the camera maker to position the camera lens with respect to the fixed focal-plane with a high degree of confidence that optimum performance will be achieved provided that the focal-plane is placed at a distance from the rear vertex of the lens corresponding to the value of the back focal distance, BF, for best average definition.

The measured value of the equivalent focal length, EFL, is valid as a true scale-factor for use in interpreting transverse distances in the central region of the negative. For the outer regions of the negative, the relation

$$f = EFL = r_\beta \cot \beta \quad (2)$$

yields varying values of EFL. It is customary to attribute this value to distortion, D_β, defined by the equation

$$D_\beta = r_\beta - f \tan \beta \quad (3)$$

where EFL is written f for brevity. Values of D_β are determined from the measurements of r_β made on the original test negative. It frequently happens that D_β so defined may reach a high value at large values of β and produce intolerable error for the given scale-factor because of wide variation in the measured magnitude of equal areas located in different regions of the negative. This may be minimized by selecting a value of f which when used in Equation 3 equalizes the magnitude of the maximum positive and the maximum negative distortion. This particular value of f is designated f_c or calibrated focal-length, CFL.

Values of the resolving power are read from the images registered on the negative in the plane of best average definition. At this Bureau, high-contrast line charts are used and values of resolving power for tangential and radial are reported at each angular interval. Values are given in lines-per-millimeter and indicate that the given pattern and all coarser patterns are clearly resolved. The values of resolving power vary with contrast of target and emulsion used to register the image. Knowledge of the measured value of the resolving power is of interest to the lens user in that it gives an indication of the quality of definition that can be obtained with the lens. High values indicate good definition. The foregoing measurements which are made on the precision-lens testing camera are made on lenses not mounted in cameras. When the values obtained indicate that the lens is suitable for use in a precision-mapping camera, the lens is mounted in its camera and returned for calibration on the camera calibrator.

2.1.2 *Calibrations on lenses mounted in precision-type cameras*

The camera calibrator is equipped with 25 collimators consisting of four arrays of collimators spaced at 7.5° intervals. The four arrays make successive angles of 90° to form a cross-shaped arrangement. The central collimator is common to all. This device permits the valuation of the distortion at 7.5° intervals for four separate radii of the picture area. In addition, the device is used for locating the principal-point of collimation and the relative positions of the four collimation-markers mounted for registry in the focal plane. A schematic drawing of a typical test negative is shown in Figure 1. The location of the collimation index markers, designated *A*, *B*, *C*, *D* are registered on the photographic plate at the same time as the images of the collimator targets along the radii, designated *I*, *II*, *III*, and *IV*. While a single negative contains all of the information necessary for the calibration of a precision-camera, two are made with the camera rotated 180° in azimuth between exposures and the measured results averaged to insure accuracy.

With this device, the equivalent and calibrated focal-lengths of the lens are determined for the actual focal-plane of the camera. In addition, values of the radial distortion are determined for four radii spaced at azimuths 0°, 90°, 180°, and 270°.

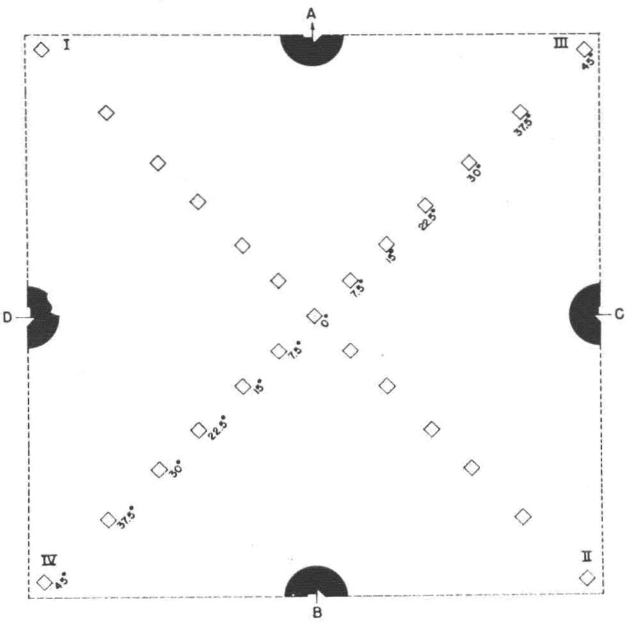

FIG. 1. Schematic drawing of test negative obtained with camera calibrator.

Variations in the value of D_β for a given value of β with azimuth indicate the presence of radial asymmetric-distortion.

To illustrate the effect of radial asymmetric-distortion measured values of the distortion D_β for β ranging from 0° to 45° for four azimuths are shown for two lenses in Table 1. In this table, it is clear that for lens No. 1, the values of D_β for a given value of β show relatively small variation with ϕ, the azimuthal angle: moreover the average departure $\overline{\Delta D_\beta}$ from the average $\overline{D_\beta}$ is not appreciably greater than the probable error of measurement. On the other hand, the values of D_β for a given value of β for lens No. 2 show marked variation with ϕ. In addition, the average departure $\overline{\Delta D_\beta}$ from $\overline{D_\beta}$ is in two instances greater than $\overline{D_\beta}$; and $\overline{\Delta D_\beta}$ is also much greater than the probable error of measurement.

If the target images for radii 0° and 180° do not fall in a straight line, tangential-distortion is indicated. Also the failure of images for radii 90° and 270° to fall in the same straight line indicates tangential-distortion. The use of the two negatives taken at azimuth 0° and 180° of camera rotation about its axis increases the accuracy of determination of tangential-distortion.

The function of the collimation markers is to locate the position of principal-point of autocollimation on each negative produced by the camera in use. Consequently extreme care must be taken in the design and installation of such markers to ensure their precise positioning and to permit precise measurement of their separations and locations relative to each other. Their configuration simplifies the orientation of successive negatives relative to each other; indicates direction of flight; and the measured separation of their images on the film permits a comparison with the separations listed in the calibration report for use in checks on differential film shrinkage. Close tolerances are usually set on the location of these markers both for the angle between the lines joining opposite pairs of markers and the position of the intersection point (center of collimation) of these lines and the principal-point of autocollimation. Because of these close tolerances, it is usually necessary to adjust the location of the markers following preliminary calibration in such a manner that the prescribed tolerances are satisfied. Following such adjustment, the calibration is repeated to determine whether or not the requirements have been met.

The platen is checked for flatness in the course of calibration. Tolerances for flatness are usually set as low as feasible because departures from flatness introduce appreciable amounts of distortion. In addition, measurements of the departures from paral-

TABLE 1. VARIATION OF THE DISTORTION D_β REFERRED TO THE CALIBRATED FOCAL-LENGTH WITH ANGULAR SEPARATION β FROM THE AXIS AND AZIMUTHAL ANGLE ϕ ABOUT THE AXIS

These values are shown for wide-angle lens No. 1, which has low asymmetric-distortion (part a), and lens No. 2 which has appreciable asymmetric-distortion (part b). Values of the average $\overline{D_\beta}$ and the average departure from the average $\overline{\Delta D_\beta}$ are also given. All values are expressed in microns.

(a) *Lens No. 1* D_β *at* β =							
β *Azimuth*	0°	7.5°	15°	22.5°	30°	37.5°	45°
degrees							
0	0	2	4	−2	− 9	3	−11
90	0	2	1	−9	− 9	3	− 8
180	0	2	−1	−5	− 6	6	− 6
270	0	2	2	−8	− 7	6	− 1
$\overline{D_\beta}$	0	2	2	−6	− 8	5	− 6
$\overline{\Delta D_\beta}$	0	0	±1	±2	± 1	± 2	± 3

(b) *Lens No. 2* D_β *at* β =							
0	0	−1	−1	−2	−15	−12	−22
90	0	−2	−5	0	1	16	28
180	0	−1	−5	−4	− 6	9	27
270	0	0	2	2	− 3	0	−10
$\overline{D_\beta}$	0	−1	−2	−1	− 6	3	6
$\overline{\Delta D_\beta}$	0	0	±3	±2	± 5	± 9	±23

lelism of surfaces of the filter mounted on the front of the lens are made. This is done because a filter whose surfaces are appreciably out of parallel behaves like a thin prism and introduces both radial, asymmetric, and tangential-distortion into the final negative.

It must be mentioned that the foregoing calibrations are intended for precision-type mapping cameras, which do not have the collimation index markers and focal-plane located in detachable magazines. In addition, the calibration negatives are made without activating the shutter mechanism. Consequently, it is necessary that cameras submitted for this type of calibration should be in such condition that the shutter can be maintained in the open position during test.

3.0 CALIBRATION OF LENSES USED AT FINITE DISTANCES

In general, the lenses used at finite distances include such a wide range of sizes and focal-lengths that it is impracticable to use photographic methods because of space limitations. It is therefore customary to use a visual optical bench for such lenses.

3.1 CALIBRATIONS USING THE VISUAL OPTICAL BENCH

Measurements commonly made on the visual optical bench (21) include focal-lengths; back and front focal-distances; lens thickness; nodal-point separation; and distortion.

The optical bench, presently in use at the National Bureau of Standards, consists of a set of bench ways upon which are mounted slides carrying a viewing microscope and nodal-slide assembly. A collimated beam of light is provided by a parabolic mirror mounted at one end of the bench ways. Length measurements are made with respect to a standard scale mounted beside the bench ways or in the case of distortion with respect to a transverse scale that indicates sideways displacement of the viewing microscope. The nodal slide assembly upon which the lens under test is mounted is provided with a variety of adjustments for positioning the rear nodal-point of the lens in the vertical axis of rotation. In addition, provision is made for measured angular displacements of the optical-axis of the lens with respect to the axis of the collimated beam from the mirror.

To measure the equivalent focal-length of a lens, the lens is so positioned that its rear nodal-point is located in the vertical axis of rotation of the nodal-slide and the entire assembly moved along the bench ways until the illuminated target located in the focal-plane of the lens is imaged by the lens in the object-plane of the viewing microscope. The distance separating the image formed by the lens and its rear nodal-point is the equivalent focal-length, *EFL*, of the lens. The distance separating the image and the vertex of the back surface of the lens is the back focal-distance, *BF*.

A simple focal-length determination usually suffices where the user is concerned only with the scale-factor in the image for very distant objects and is not concerned with distortion.

For lenses used at finite distances, the front equivalent focal-length, front focal-distance (*FF*) nodal-point separation (*NPS*), and lens-thickness (*T*) are also measured. These front and back equivalent focal-lengths can usually be regarded as equal. These quantities are related as follows:

$$2\,EFL + NPS = BF + FF + T \qquad (4)$$

It is necessary to have reliable values of the foregoing quantities for proper positioning of object-plane, lens, and image-plane in a camera used at finite distances at specified values of the reduction ratio ($1/M$) where M is the ratio of object-to-image size, shown in Figure 2. In such instances, the object-distance d_o and image-distance d_i are given by the following formula:

$$d_o = f(M + 1) \qquad (5)$$

$$d_i = f\left(1 + \frac{1}{M}\right) \qquad (6)$$

and the distance D separating object and image planes is

$$D = d_o + d_i + NPS = \frac{f}{M}(M + 1)^2 + NPS \qquad (7)$$

If the lens is intended for use in highly precise copying or projection work, the values of the distortion in the image-plane at one or more specified values of the reduction ratio are also measured.

Values of the resolving power can also be determined with the visual optical bench. These values are useful in indicating the probable performance of the lens although they are likely to be appreciably higher than those determined by photographic means.

4.0 Miscellaneous Calibrations

In the foregoing sections, a brief account of calibrations that are frequently performed at the National Bureau of Standards is given. In addition, many calibrations are performed of a less routine nature. These calibrations include items such as determination of geometric *f*-number, *T*-number, lens transmit-

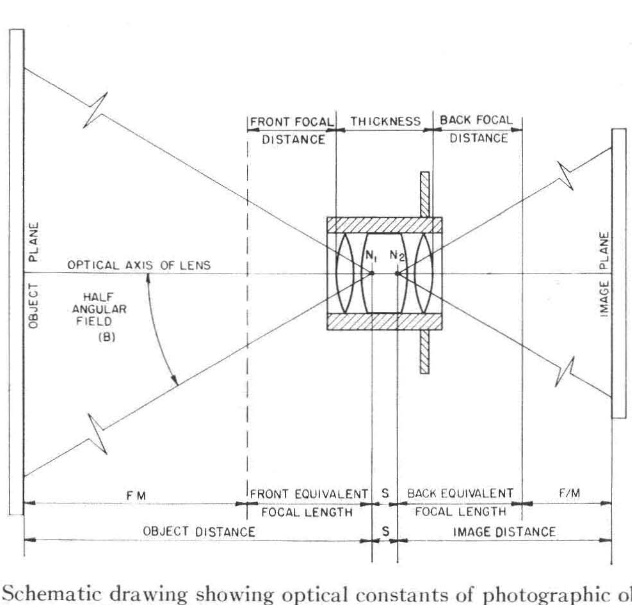

FIG. 2. Schematic drawing showing optical constants of photographic objective and the relation between object and image distances.

tance, relative illumination in the focal-plane, longitudinal spherical and chromatic-aberration, sine-wave response, and many tests of a specialized nature.

5.0 Fees for Calibration

The calibrations described in the foregoing sections are performed on a fee basis with the fee determined by the actual cost of labor and materials used in the work. Calibrations that are frequently performed are usually on the basis of a fixed fee which are listed in the Test Fee Schedule published in the *Federal Register*. The schedule presently in use was published Apirl 8, 1961 in Volume 26, Number 67 of the *Federal Register*. The fee for calibrations of a specialized nature are based upon actual labor costs and computed at the time of the test.

These calibrations are performed as promptly as possible following receipt of the material in condition for test; a specific request authorizing the test; and instructions describing the nature of the test required. It is usually possible to complete a given calibration within three weeks following recipt of the material. Further information on specific details may be obtained on request from the Refractometry Section, Metrology Division (2.2), National Bureau of Standards, Washington 25, D. C.

6.0 List of Publications by Members of Staff of the NBS that Pertain to the Problem of Lens and Camera Calibration

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15. Rosberry, F. W., "Effect of Object Frequency on Focal Position of Four Photographic Objectives," *J. Research NBS* 57, 17 (1956) RP2688.
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17. Washer, F. E. and Scott, L. W. "Influence of the Atmosphere upon the Precision of Telescope Pointing," *J. Research NBS* 39, 297 (1947) RP1829.
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*Image Aberration**

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INTRODUCTION

ABERRATION in a photogrammetric system is the displacement of an image equal to the distance the system travels in the time it takes the image forming light to pass from the lens to the light sensitive surface, or the displacement of an object equal to the distance the object travels in the time it takes the image forming light to pass from the object to the lens. Aberration is the sum of the displacements if both the object and photogrammetric system are in motion. The total displacement, therefore, varies with the image distance, object distance, image velocity vector, and object velocity vector.

The angular deviation S subtended by the total image displacement arising from the sum of the object and photogrammetric system motion, on the other hand, depends only on the ratio of the velocities times the sine of the angle enclosed between the direction of motion and the direction of the image-object line. This is expressed with the equation

$$S = \frac{v}{V} \sin \theta$$

where

v = the velocity of the system or object
V = the velocity of light.

Assuming the direction of motion is perpendicular to the direction of the object and the velocity of the system is one mile per second,

$$s'' = 1.''0$$

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