ENGLISH VIEWPOINT: LENS TESTING AND CAMERA CALIBRATION

J. E. Odle, F.R.G.S., Williamson Manufacturing Co., Ltd., London, England

INTRODUCTION

THE following organizations are interested in camera calibration in the United Kingdom: Royal Aircraft Establishment, Directorate of Colonial Surveys, Directorate of Military Survey, Director General of Ordnance Survey, Ministry of Supply, National Physical Laboratory, Williamson Manufacturing Co. Ltd.

J. E. ODLE

The National Physical Laboratory and the Royal Aircraft Establishment have equipment set up for instrumental calibration and the Service organizations undertake field surveys. In practice, the production calibration of survey cameras is carried out by Williamsons, whose standards and methods have been agreed with the above bodies. The experience and requirements of the two major U.K. commercial air survey organizations are available.

Prior to the extensive development of instrumental methods of plotting, users of air photographs were content to accept calibration data from the authority, applying the information quantitatively to their particular projects. Today they regard calibration as a qualitative certificate of fitness for specification mapping. The conscientious manufacturer must therefore explain the standards he sets for his instruments, and the effect which manufacturing tolerances will have on those standards.

CALIBRATION AND TESTING

Every component of the instrument which contributes to the calibration data should be tested, and by means which are approximate to normal usage. Limits of accuracy in measurement techniques ought to be considerably less than the permitted tolerances. Photographic records are mostly used since we find they make checking operations simpler, and provide a permanent and indisputable record of the calibration state at the time of measurement. Visual methods are doubtless equally effective but require more administrative time, and in the case of very minute measurements, differences arise between visual and photographic characteristics. U.K. techniques are based on the use of universal calibration instruments owing to the range of lenses used.

For resolution assessment, the low contrast target methods are used exclusively, and are explained in Appendix "A" of this paper. These methods approximate to the actual usage of air photography, and provide an acceptable method for comparison of the performance of lenses.

Our camera calibration methods are described fully in Appendix "B" of this paper.

These methods and standards are acceptable to the organizations operating in the United Kingdom, and are giving good answers in the instrumental plotting field, at all scales.

STANDARDS

Every improvement in design and manufacture reduces the cost of fixing the photographs to the ground. Broadly speaking, modern instruments, properly constructed, are capable of giving the air surveyor nearly the accuracy which is practicable in air survey.

The Multiplex method requires a very high instrumental standard to maintain the simple bridging techniques, and in the United Kingdom our biggest effort has been to ensure consistency of optical performance as between one camera and another. Since the cost, in terms of capital equipment and manufacturing control for these highly specialized survey instruments is very considerable, it is as well for users not to press the constructors beyond the limits needed.

In automatic plotting instruments a standard radial distortion is assumed and corrected for. Non-standard cameras may well give worse results than having no compensation at all.

There are other image distortions which are essentially functions of manufacturing accuracy, and we endeavor to hold asymmetry of the 6″ wide-angle lens system to 30 seconds or below.

Sharp and Hayes have concluded that a bent axis of one minute, equivalent to 18 microns of tangential, can be caused by displacing the surface of one element by 15 microns, or .0006″. To maintain an angular accuracy of 30 seconds consequently requires lens edging and centration of the highest order. Normality of focal plane seatings, lens seatings and lens mount diameters require machining tolerances of $\pm .0001''$ or 2.5 microns.

If we examine the displacement by 30 seconds of a point on a single photograph at the focal plane using a 6″ lens, this amounts to .022 mm. on axis, or .044 mm. at 45°. Assuming a flying height of 30,000 feet, this is equivalent to a linear displacement of 4.36 ft. on axis or 8.73 ft. at 45°.

DIRECTION OF DEVELOPMENT

In the United Kingdom the trend is towards optical systems which are inherently free from distortion. Messrs. Ross have produced for Williamson air cameras two new lenses in which theoretical radial distortion has been reduced to a new low level.

Concurrent with the construction of lenses, wholly new methods of mounting and testing have been jointly devised by Williamson and Ross technicians.

The 12″ F/5.6 survey lens has radial distortion not exceeding $\pm .02$ mm. for the $9'' \times 9''$ format, and is giving very satisfactory results for large scale Ordnance Survey revision. Series production of this lens has commenced. For wide-angle work Ross have produced a new lens of 6.3″ (16 cm.) focal length working at f/5.6 and having radial distortion for the $9'' \times 9''$ format not exceeding $\pm .02$ mm.

The prototype lens has passed laboratory and flying trials satisfactorily, and the first production batch will be available early this year. Resolution of both of these lenses is better than previous types.

SUMMARY

(i) Existing calibration methods satisfy United Kingdom users, and are controlling production to high standards.

(ii) Development is towards elimination of radial errors of design and decentration errors of manufacture, so far as is practicable. New wide-angle lenses show promise, a slight increase in focal length gives substantially reduced radial distortion characteristics, and new methods of lens mounting are reducing errors of asymmetry. It is felt we are approaching the limiting accuracy of the internationally known wide-angle systems, and if greater accuracy is required a recasting of accepted ideas on format size and focal length will be necessary.

ACKNOWLEDGMENTS

Royal Aircraft Establishment, Farnborough, and Ministry of Supply for material on resolution testing. The author acknowledges the assistance of Mr. Chitty, Williamson Mfg. Co. Ltd. for checking figures and assembling material on calibration techniques.

APPENDIX "A"

CALIBRATION OF CAMERAS IN THE WILLIAMSON PHOTOGRAMMETRIC LABORATORY

PRINCIPAL POINT LOCATION

The location of the principal point is established by auto-collimation. The camera is placed on a stand in a vertical position with the register glass accurately levelled and a microscope placed on the register glass directly over the center fiducial mark. The microscope is designed with a transparent mirror in the center, which can be illuminated from the outside by daylight or artificial sources. When this is done, an image of the fiducial mark is projected through the camera lens, with shutter open, to a surface silvered mirror placed directly below the lens. Since the surface silvered mirror is also accurately level, the image is returned via the camera lens, to be formed at the register glass surface. By floating the lens in a horizontal plane, the fiducial mark and its reflected image, are made coincident.

Providing the camera and lens construction are accurate, the center fiducial mark may now be assumed as the principal point of the camera. The probable error of this setting is assumed to be 12 seconds of arc. With a 6″ focal length camera this would amount to approximately 0.01 mm. and increasing to 0.02 mm. with a 12″ focal length.

DETERMINATION OF PRINCIPAL DISTANCE AND DISTORTION

The essential of principal distance and distortion determination is that a beam or ray of light is made to enter the lens at accurately known angular intervals over the complete field of the camera, usually across the two diagonals of the format. The positions, on the focal plane, of the resultant images are then measured, and the desired information calculated from the known angles and measured distances.

These essential conditions are achieved in the Williamson Laboratory by mounting the camera, with the optical axis horizontal, on a goniometer so that the whole camera may be swung about the node of the lens to an accuracy of five seconds of arc.

A large aperture collimator is arranged at the same level as the camera to form an image at the focal plane, and a glass photographic plate is pressed into contact with the register glass. Commercial Kodak 12″×10″ panchromatic plates are found to be adequate providing suitable pressure is used to ensure perfect contact with the register glass.

The camera shutter is fired at each predetermined angle thus making a photographic record of the line of images. The resultant exposed plate is carefully processed, and the linear positions of the images measured on a Cambridge Universal Measuring Machine.

The ensuing calculation follows closely that laid down by Hotine in "Calibration of Surveying Cameras—Professional Paper No. 5" published by His Majesty's Stationery Office. The sketch, Figure 1, represents a section through the camera in a vertical plane, such that N is the internal perspective center, A and B are the two images whose angles α and β are known, O is the center image. The principal point is assumed to be either side of the line joining A and B such that a line normal to AB passing through the principal point cuts AB at P. Distances a and b are measured from the photographic plate.

By applying the rule of sines to triangle ANO and BNO

$$\frac{a}{\sin \alpha} = \frac{PN}{\sin (90 - \theta)}$$

$$\therefore \quad a \cos \theta = PN \sin \alpha$$

similarly

$$\frac{b}{\sin \beta} = \frac{PN}{\sin (90 - \phi)}$$

$$\therefore \quad b \cos \phi = PN \sin \beta.$$

Thus:

$$\frac{b \cos \phi}{a \cos \theta} = \frac{PN \sin \beta}{PN \sin \alpha} \quad \text{whence} \quad \frac{\cos \phi}{\cos \theta} = \frac{\operatorname{cosec} \alpha}{\operatorname{cosec} \beta} \times \frac{a}{b}.$$

Choose an auxiliary angle λ such that:

$$\frac{a \operatorname{cosec} \alpha}{b \operatorname{cosec} \beta} = \tan (45 + \lambda).$$

Then

$$\tan (45 + \lambda) = \frac{\cos \phi}{\cos \theta}. \tag{1}$$

By expanding

$$\frac{\tan 45 + \tan \lambda}{1 - \tan 45 \tan \lambda} = \frac{1 + \tan \lambda}{1 - \tan \lambda} = \frac{\cos \phi}{\cos \theta}.$$

Thus:

$$\cos \theta(1 + \tan \lambda) = \cos \phi(1 - \tan \lambda)$$

$$\cos \theta + \cos \theta \tan \lambda = \cos \phi - \cos \phi \tan \lambda$$

$$\cos \theta \tan \lambda + \cos \phi \tan \lambda = \cos \phi - \cos \theta$$

$$\tan \lambda(\cos \theta + \cos \phi) = \cos \phi - \cos \theta$$

$$\tan \lambda = \frac{\cos \phi - \cos \theta}{\cos \phi + \cos \theta}$$

$$= -\frac{2 \sin 1/2(\phi + \theta) \sin 1/2(\phi - \theta)}{2 \cos 1/2(\phi + \theta) \cos 1/2(\phi - \theta)}$$

$$= \tan 1/2(\theta - \phi) \tan 1/2(\theta + \phi)$$

or

$$\tan 1/2(\theta - \phi) = \cot 1/2(\theta + \phi) \tan \lambda.$$

Since from Figure 1

$$1/2(\theta + \phi) = 1/2(\alpha + \beta) \quad (2)$$

$$\tan 1/2(\theta - \phi) = \tan \lambda \cot 1/2(\alpha + \beta). \quad (3)$$

Thus θ and ϕ are readily found from (2) and (3).

To calculate the principal distance f:

$$f = PN = AN \cos \theta. \quad (4)$$

From Figure 1 using rule of sines:

$$\frac{a + b}{\sin(\theta + \phi)} = \frac{AN}{\sin(90 - \phi)} = \frac{AN}{\cos \phi}$$

$$\therefore \quad AN = \frac{(a + b) \cos \phi}{\sin(\theta + \phi)}. \quad (5)$$

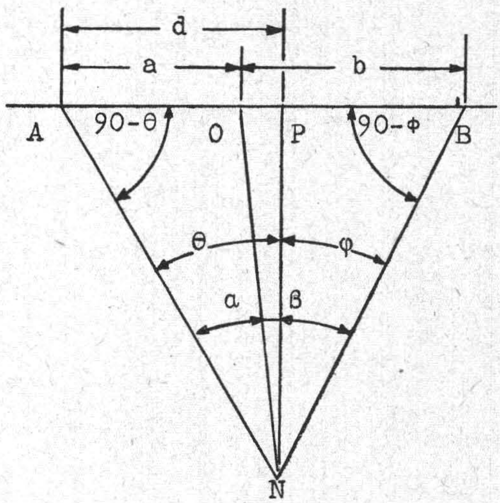

FIG. 1

Substituting (5) in (4)

$$f = \frac{(a + b) \cos \phi \cos \theta}{\sin(\theta + \phi)}$$

or referring to (2)

$$= \text{cosec } (\alpha + \beta)(a + b) \cos \phi \cos \theta$$

but since $\alpha+\beta$ can be made identical

$$f = \text{cosec } 2\alpha(a + b) \cos \phi \cos \theta.$$

Similarly, the co-ordinate of the principal point is given by

$$d = AN \sin \theta.$$

By substituting (5) for AN

$$d = \text{cosec } 2\alpha(a + b) \cos \phi \sin \theta.$$

The calculation of principal distance in the foregoing formulae presupposes that the images of A and B are in their true positions, i.e. distortion free. Further it is desirable to choose points when α and β are reasonably large and in a zone where the distortion is not changing rapidly; for example 35° off axis with a Ross 6″ $f/5.5$ Wide-Angle Survey Lens. It follows therefore that a correction must be made to the value of f to produce the required distortion at the angular zone used for the calculation.

The distance d when calculated will give the position of P; distortion calculations are then made relative to this point, which should agree with the center fiducial mark previously positioned by autocollimation within ±.02 mm.

PRESENTATION OF DISTORTION

The method of presenting the distortion varies considerably with different organizations, and although it would be very convenient to have a standard method it is not essential. This Laboratory has reached agreement with the lens manufacturer and the Ministry of Supply, with the result that for the Ross 6″ $f/5.5$ Wide-Angle Survey Lens in particular, a standard curve has been drawn from a mean of 20 cameras calibrated by this Laboratory. This standard has a displacement of −0.16 mm. for the zone 35° from the axis. The negative sign indicates that the image is displaced away from the principal point.

The procedure with the aid of this curve is to adjust the principal distance of a camera until the best fit is obtained with a maximum tolerance of ± 0.02 mm. from the standard curve, to a maximum angle of 43°. Beyond this angle the distortion changes very rapidly and cannot be measured with any certainty. The portion of the picture outside this angle represents about $2\frac{1}{2}\%$ of the total area, and assuming normal lateral overlaps is not likely to be troublesome.

CALCULATION OF DISTORTION

The value of f (principal distance) calculated from the formula previously described is applied to calculate the true position for any one ray. As the camera is calibrated across two diagonals in this Laboratory, a mean of the two values is taken.

The angles of the incident rays are first corrected by the amount the center point O deviated from P, which is in fact $\frac{1}{2}(\theta-\phi)$. From Figure 1 it will be seen that if the corrected angles are θ or ϕ, their true positions will be given by $f \tan \theta$ or, $f \tan \phi$. The measured positions of the emergent rays are then corrected by the distance OP. The difference between this value and that given by $f \tan \theta$ or $f \tan \phi$ is the distortion of the lens.

THE CALIBRATION REPORT

The Calibration Report issued by this Laboratory is intended to assure the customer that the camera's optical performance is up to standard. The report includes particulars of the filter and register glass fitted. The principal distance quoted is accompanied by the resultant distortion figures and the angular zone or distance off axis used in the calculation of the principal distance.

The curves plotted from the distortion figures are attached to the report.

TOLERANCES—ROSS 6″ $f/5.5$ WIDE-ANGLE SURVEY LENS

It has previously been mentioned that a variation from the standard distortion curve must not exceed ± 0.02 mm. This variation from the standard is applied to the mean curve obtained from any camera. The asymmetry of distortion of that camera should not exceed ± 0.02 mm. from that mean. In practice it is invariably found that the symmetry and distortion combined are sufficiently controlled to fall within the tolerance of ± 0.02 mm. from the standard.

Variation of principal distance is not controlled for this lens, but it has been found that they do not exceed the range of 152 mm. to 155 mm.

ROSS 12″ $f/5.6$ E.M.I. LENS

The distortion for this lens is nominally zero, but a tolerance of ± 0.02 mm. to a maximum angle of 25° off axis, amounting to $97\frac{1}{2}\%$ of the picture area is considered permissible.

APPENDIX "B"

RESOLUTION TESTS OF AIR CAMERAS IN THE WILLIAMSON PHOTOGRAMMETRIC LABORATORY

SUMMARY

The resolution of air cameras may be quite conveniently quoted in units of "Ground Resolution." The term means that a Ground Resolution of x indicates that an object of 1 ft. width on the ground will be resolved by the camera flown at an altitude of x ft.

The test chart used for measurement of resolution is composed of Cobb objects decreasing in size in 10% steps, with a contrast of 0.2 between the objects and the background.

The lens under test is first focussed for minimum fringe on a high contrast graticule in the focal plane of a collimator. The graticule is then replaced by the low contrast resolution test object, which is photographed on Kodak P.300 plates or Super XX film through a minus blue filter unless otherwise stated, at angular intervals across the field. The negatives are then read under 16 × magnification. The smallest groups resolved are a measure of the resolving powers on radial and tangential lines.

A Cobb object consists of two luminous lines, three times as long as they are wide, and separated by a distance equal to their width.

Let the width of a line on the smallest group resolved on the test object be $\Lambda/2$.

Then the size of detail resolved $=\Lambda$ and the angular resolution $\theta=\Lambda/F$ where F is the focal length of the collimator. Hence the angular resolution depends only on the group resolved on the test object, and is independent of f or ϕ; where

f = focal length of the lens under test

and ϕ = angle of obliquity of the test object

let λ = size of detail resolved in the focal plane of the lens under test,

and let the suffixes (r) and (t) indicate resolution on radial and tangential lines respectively.

Then

$$\lambda(r) = \frac{\Lambda(r)}{F} \times f \sec \phi$$

and

$$\lambda(t) = \frac{\Lambda(t)}{F} \times f \sec^2 \phi.$$

We define the resolving power of the lens as

$$R = \frac{f}{\lambda} = \text{(focal length in mms)} \times \text{(resolving power measured in lines/mm)}.$$

This is equal to $1/\theta$ only when the object photographed is on axis.

In general

$$R(r) = \frac{1}{\theta(r)} \cos \phi$$

$$R(t) = \frac{1}{\theta(t)} \cos^2 \phi$$

R gives immediately the size of detail resolvable on the ground at a given height; independently of the focal length of the lens.

$$R = \frac{\text{Vertical Height}}{\text{Size of ground detail}} = \text{Ground resolution.}$$

The resolution results are plotted in the form log R against angle of obliquity. The logarithmic scale is used as it enables the same scale to be used for lenses of all focal lengths, and facilitates plotting since the steps on the test object give equal increments on the logarithm.

Chairman Howlett: Mr. Odle was extremely kind to collect this information on English practice and present it to us. I was hopeful in the latter part of his talk, he might introduce something contentious, but the discussion still seems to be on the verge of breaking down into a mutual admiration society, which is hardly what was intended in the first place.

It appears that considerable progress must have been made in the past year or two, outside of formal meetings, in bringing us all to a more satisfactory point of view and with better hope of reaching a general agreement.

We now have the great pleasure in having a few remarks from an authority in this field who certainly needs no introduction whatsoever to a North American audience. His distinctions, both scientific and political, have reverberated around the world. It is a great privilege to call Professor Schermerhorn for a few remarks.