CALIBRATION OF AN AMATEUR CAMERA FOR UNIVERSAL CLOSE-RANGE APLICATIONS

Sanjib K. Ghosh, Monir Rahimi and Zhengdong Shi
1335 Pav. Casault, Laval University
QUEBEC G1K CANADA

Abstract

Calibration plays an important role in application of non-metric cameras for metric stereorestitution tasks. An IBM-PC computer operated procedure has been developed for such an analytical calibration of cameras. The geometric concept used and mathematical models developed for this procedure are described. An exemple is presented with regard to an amateur camera calibrated for four focal lenght settings by using convergent multi-photo configurations. The calibrated focal lenghts and the corresponding lens distortion data are presented for the various cases, from which parameters for any other specific case can be obtained by interpolation. The experience and the results indicate that the procedure is economical and convenient for most close-range applications demanding precision measurements.

Introduction

With more and varied use of photogrammetry for precision close-range applications, camera calibration plays an important role whereby non-metric cameras yield results enough to challenge metric cameras in view of their cost-effectiveness. Most realistic approaches for the calibration of a non-metric camera can be classified into two groups: (a) on-the-job calibration, and (b) self-calibration.

On-the-job calibration has been noted to require an object space control network (Anderson et al, 1975), where the number of necessary control points would be directly proportional to the desired number of involved parameters.

Unlike the classical procedures, the self-calibration concept initiated by Brown (1972) is based solely on the image point measurements without requiring absolute ground control. A strong geometrical configuration of multiple photographs over the same field of unknown object points would be desirable (Ghosh, 1988). Furthermore, self-calibration can also be "on-the-job". One would easily see that self-calibration procedure has more advantages (Moniwa, 1977). This is why self-calibration is more welcome in practice. Oftentimes a close-range job with an amateur camera would require an unpredictable focal-lenght setting. This would necessitate a clear understanding of the interior geometry for the specific case. Assuming that if the camera could be calibrated for multiple focal-leght settings (with regard to respective object distances), in pratice all interior orientation parameters for any other specific case would be obtainable by simple interpolation. The above would give the rationale behind the present study.

Basic Mathematical Models

The self-calibration approach is based on the augmentation of collinearity condition equations. There are however some differences among the mathematical models used in the self-calibration of various organizations. These differences are mainly due to the different ways of modeling the lens distortions, the film deformations and the consideration of weighting the parameters in calibration (El-Hakim, 1979; Adiguzel, 1985; Fryer, 1984).

The basic mathematical models used in this study (developed from the concept of Brown, 1972) are as follows:

$$\bar{x} + dV_x = -f \frac{M_{11}(X-X_0) + M_{12}(Y-Y_0) + M_{13}(Z-Z_0)}{M_{31}(X-X_0) + M_{32}(Y-Y_0) + M_{33}(Z-Z_0)}$$

$$\bar{y} + dV_y = -f \frac{M_{21}(X-X_0) + M_{22}(Y-Y_0) + M_{23}(Z-Z_0)}{M_{31}(X-X_0) + M_{32}(Y-Y_0) + M_{33}(Z-Z_0)} \qquad (1)$$

Where,

dV_x, dV_y are the corrections for lens distorcions,

$$dV_x = \bar{x}\,(k_1 r^2 + k_2 r^4 + k_3 r^6) + [P_1(r^2 + 2\bar{x}^2) + 2P_2\bar{x}\bar{y}]\,(1 + P_3 r^2)$$
$$dV_y = \bar{y}\,(k_1 r^2 + k_2 r^4 + k_3 r^6) + [P_2(r^2 + 2\bar{y}^2) + 2P_1\bar{x}\bar{y}]\,(1 + P_3 r^2)$$

x and y are photo-coordinates with fiducial reference;

x_0, y_0 are the photo-coordinates of the principal point with fiducial reference;

f is the calibrated focal length;

k_1, k_2, k_3 are the coefficients for radial lens distortion model (partly polynomial stemmed);

P_1, P_2, P_3 are the coefficients for decentering lens distortion model (partly polynomial stemmed);

M's are the elements of the orientation matrix;

X, Y, Z are the ground coordinates of the object points; and

X_0, Y_0, Z_0 are the ground coordinates of the camera perpspective center.

After linearizing (1), and considering the other weighted function constraints for all the parameters, the mathematical model can be written as:

$$V + A_1\Delta_1 + A_2\Delta_2 + A_3\Delta_3 + W = 0 \qquad (2a)$$
$$V_1 + \Delta_1 + W_1 = 0 \qquad (2b)$$
$$V_2 + \Delta_2 + W_2 = 0 \qquad (2c)$$
$$V_3 + \Delta_3 + W_3 = 0 \qquad (2d)$$

Where,

V : residual vector of mage coordinates;

Δ_1: unknown external orientation parameters (x_0, y_0, f, k_1, k_2, k_3, P_1, P_2, P_3);

Δ_2: unknown interior orientation parameters;

Δ_3: unknown object point coordinates;

A_1, A_2, A_3 are the corresponding coefficient matrices;

V_1, V_2, V_3 are the rèsidual vectors of the three types of pseudo observations Δ_1, Δ_2, Δ_3, respectively; and W, W_1, W_2, W_3 are the misclosure vectors in the equations.

The final estimations of the unknown parameters are based on the principle:

$$V^t P V + V^t_1 \underline{P}_1 V_1 + V^t_2 \underline{P}_2 V_2 + v^t_3 \underline{P}_3 V_3 \dots\rightarrow \min.$$

Where,

P is the wheight matrix of image coordinates, and

$\underline{P}_1$, $\underline{P}_2$, $\underline{P}_3$ are the weight matrices of pseudo observations. With regard to the present study, the following characteristics may be pointed out:

(1)Radial lens distorcion is formulated by the well known odd-power polynomials. More complex film deformations are not considered, because the photo format is small (56 x 56mm). The linear part is automatically contained in the photo coordinate transformation. Usually, the effects of film deformation on image coordinates are very small fòr such small formats (Hatzopoulous, 1985). Nonetheless, effects of irregular unflatness of film may still remain. However, multiple convergent photography would considerably minimize the effects and thus would lead to acceptable closures and accuracies.

(2) All unknown parameters are treated as pseudo observations. This includes the interior orientation parameters as well. Proper wheights can be assigned in pratice to these pseudo observations.

(3) The à priori wheights used in a case exemplified here are listed in Table 1. These are based on previous experience in view of their geometric configurations and realistic reliabities.

The above characteristics have the following special advantages:

(a) All image point coordinates, including the points appearing only on two photos can be used. These are the only known (through observations) data.

(b) Good geometric conditions plus proper input of weights can reduce or even eliminate annoying effects of correlation between various parameters.

(c) Interraction amongst various "standards" is avoided (eg., geodetic standard of ground control; manufacturers' standards for photogrammetric equipament and camera, etc.).

(d) Absolute ground control need not be established. Approximate values are necessary to initiate iterative solution procedures.

Data Acquisition

The case of a specifc camera (one Rollei SLX, f=80mm) is presented here as an example to illustrate the concepts and developments. the camera was calibrated for four focal-lenght settings corresponding to four different object distances (0.25 m, 1.0 m, 2.5 m, 7.0 m) with a view to its use on varying objects distances. In the case of 0.25 m, an attachment had to be used for extending the lens tube in order to get a clear focus on the object (targets).

Highly convergent photos were from four different directions around the test field in each case. For reason of simplicity and adequacy, the test field is fairly flat. However, the high tilt (φ or $\omega \cong 60$) photos provide variable Z (projection distances) at the field points giving the equivalency of a three-dimensional field for each photo (Fig.1). All of the 16 photos were on the same roll of film. Three different test ranges had to be used for the calibration because of the differences in the corresponding ground coverages; one is for 0.25 m, one for 1.0 m and 2.5 m and the last one for 7.0 m. The designs of the three ranges are similar, except that the grid dimensions are different. Each range consists of more than 40 grid points. However, during the calibration, at least 20 points, selected at random and evenly distributed over the formats in each case, were used. Theoretically speaking, only two photos were taken in each case in order to get the best possible intersection geometry and in order to compare the results from 2, 3 and 4 photos (explained later).

Photo points were measured on both Wild BC-1 Analytical Plotter and Wild STK-1 Stereocomparator. Each photo was measure twice on each instrument by approaching each points from opposite directions in order to avoid blunders as well as to overcome the effects of instrumental back-lash. The purpose of measuring the photos on the two instruments was to compare the results from different measuring tools. The maximum difference between the image coordinate values at the two instruments was 4 μm, proving thereby that data from any such comparator would be acceptable realistically. Software is available to store the image coordinates directly on disks to be used on the IBM-PC computer, with regard to any of the two instruments.

Calibration Results and Analyses

The calibration results presented here are based on the image coordinates measured with the STK-1 Stereocomparator in mono-mode. The interior orientation parameters are listed in Table 2, where one can see that in cases 2, 3, and 4, the x_o y_o are near zero. As mentioned before, in case 1. an attachment was used to obtain clear focus on the target. The x_o and y_o shifts in this case are conjectured to be due to the additional attachment, causing camera axis deviation.

According to the Gaussian optical law. the longer the object distance, the shorter should be focal distance. The f values in Table 2 (based on 4 photo network in each case) agree with this law (Fig.2). The change seems to be systematic. The data have been examined to check for statistical "goodness of fit".

The calibrated focal lenght has the best accurary (0.28 mm) in case 4, also suggesting that the camera has better focus at 7.0 m distance.

The lens distortion parameters of the camera are listed in Table 3, where one can see that the decentering lens distortions are negligible. With the photo format 56 x 56 m , the computed maximum tangential lens distortion components in x and y are less than 1 μm.

The radial lens distortion curves of this camera for different object distances (treated independently) are shown in Fig.3. Table 3 and Fig. 3 indicated that (a) The radial lens distorcions are significant in cases 1 and 2; and (b) In cases 3 and 4, the lens distortions become considerably small (negligible in case 4). In pratice, all insignificant parameters can be eliminated by assigning zero weights in the program.

In order to assess the degree of importance of lens distortion on the calibration results, the cases were studied for the following instances:

i. Calibration without considering any of the six lens distortion parameters (k_1, k_2, k_3, P_1, P_2 and P_3).

ii. Calibration by considering all the six lens diatortion parameters.

iii. Calibration by considering only k_1, k_2, and k_3.

iv. Calibration by considering only P_1, P_2 and P_3.

The results of one such (case 2) are summarized in Table 4, from which one can draw the following conclusion with regard to this particular camera:

(1) By comparing the results of instance i against the others, one would note that the accuracy is improved significantly by considering the lens distortion parameters into the calibration.

(2) The decentering lens distortion has no effect on the calibration output accuracy.

(3) The standard deviations of adjusted object coordinates, however , remain practically the same in all instances.

Tests about the effect of the lens distortions on relative orientation of two photos taken by the camera were also performed. Relative orientation was performed in two modes, one without considering the lens distortions, the other by considering the lens distortions. The results of one such test are shown in Table 5 indicating that the accuracy of relative orientation is improved significantly by considering the radial lens distortion.

In order to study the accuracy improvement with regard to the number of photos used, the calibrations in the four cases were also carried out with 4,3 and 2 photos each. Some illustrative results are presented in Table 6 and Fig.4. These indicate that with the reduction of photographs not only the redundency of observations is decreased but also the geometry is weakened, and consequently, the calibration accuracy becomes poorer.

The presented results are all from the calibrations based on the image coordinates measured at the STK-1 Stereocomparator. The calibration results from the STK-1 measurements are almost identical with those from the BC-1 observations. These are not, therefore, presented here.

A question may be raised as to why no check points were used for quality control. This self-calibration procedure does not require any field control. On the other hand, all the object points in the study were generated through grid intersections prepared at a precision coordinatograph. Their final values gave standard deviations for each coordinate less than $\pm$ 0.15 mm, indicating thereby that an excellent quality of the object point coordinates (also Table 6) is obtained.

Conclusions and Recommendations

Observations made with regard to this particular amateur camera example would give the following general conclusions:

(1) An amateur camera may have significant radial lens distortion. This distortion has strong effect when the camera is used on close-range objects.

(2) Radial lens distortion effects seem to be reduced as the object distance is increased (corresponding to shorter focal-lengths) as would be expected (Fraser and Veress, 1980).

(3) Decentering lens distortions are negligible for such amateur cameras (for all object distances).

(4) Measurement data from the STK-1 Stereocomparator and from the BC-1 Analytical Plotter would give similar calibration results, indicating thereby that any precision comparator would be adequate for such a camera calibration.

(5) The calibrated focal lengths change significantly when the object distances change. The calibrated focal length values can be interpolated (Fig.2) for specific applications with regard to the object distances.

(6) The calibration results indicate that accuracy of the calibrated focal length is somewhat related to both the object distance as well as the network geometry. However, the calibration for the farthest object distance would give the best accuracy of the focal length.

(7) It was found during the tests that among the parameters the maximum correlation in one case is 0.86 while in all the rest is less than or equal to 0.53. However, as is noticed, with the highly convergent multiphoto configuration geometry as used, such correlations are "broken". This establishes very stable and reliable geometric configuration.

(8) The attachments of the camera should be used with caution. Otherwise, it may produce annoying effects. However, such calibration would serve the purpose well as long as the outfit remains stable.

(9) To obtain a good estimation of lens distortions, object points should be widely distributed so as to cover the entire photo format in each case.

(10) All interior orientation parameters for any case than the ones used for such a calibration would be easily obtained through simple interpolations in view of the related object distances.

(11) Based on this experience it may be recommended that similar self-calibration can easily be peformed to evaluate any amateur camera before its use on metric stereo-resolution tasks. The obtainable accuracies with regard to specific parameters may be considered for specific practical applications. What counts most for photogrammetric applications is the accuracy obtained at object points. Table 6 indicates (the last three columns) that such accuracies are invariably within acceptable limits in all close range applications of such a camera.

Acknowledgement

The Natural Sciences and Engineering Research Council (NSERC), Canada provided support for most of the research through their Grant N° A-1177. Mr. Paul Trottier and Mr. Jean-Paul Agnard provided assistance at the Laval University photogrammetric laboratory. Mme Danielle Guimond assisted at the word-processor. These are all gratefully appreciated.

Reference

1. ADIGUZEL, M. (1985) "Problems Related to Three Dimension Mapping with Electron Micrographs". Ph.D. Thesis, Laval University, Quebec, Canada.

2. ANDERSON, J.M. and C. LEE (1975) "Analytical in-Flight Calibration". Photogrammetric Engg. and Remote Sensing, Vol. 41, n° 11, pp. 1337-1348.

3. BROWN, D.C. (1972) "Calibration of Close-Range Cameras". Invited paper, ISPRS XII Congress, Com. V; Ottwa.

4. EL-HAKIM, S.F. (1979) "Potencials and Limitations of Photogrammetry for Precision Surveying". Ph.D. dissertation, University of New Brunswick, N.B., Canada.

5. FRASER, C.S. and S.A. VERESS (1980) "Self-Calibration of a Fixed-Frame Multiple-Camera System". Photogrammetric Engg. and Remote Sensing, Vol. 46, N11, pp. 1439-1445
6. FRYER, J.G. (1986) "Lens Distortion for Close-Range Photogrammetry". Proceedings of the ISPRS Commission V Symposium Real-Time Photogrammetry — A new Challenge. June 16-19, Otttawa, Canada, pp. 30-37.
7. GHOSH, S. K. (1988) "Analytical Photogrammetry (2nd Ed)". Pergamon Press.
8. HATZOPOULOUS, J. N. (1985) "An Analytical System for Close-Range Photogrammetry". Photogrammetric Engg. and Remote Sensing, vol. 51, N° 10, pp. 1583-1588.
9. MONIWA, H. (1977) "Analytical Photogrammetric System with Self-Calibration and its Applications". Ph.D. dissertation. University of New Brunswick, N.B., Canada.

List of Tables

List of Figures

Table 1. Input Weights

Item			Std. Error	Weight
Interior Orientation Parameters				
$x_0, y_0, f, k_1, k_2, k_3, p_1, p_2, p_3$				unit
Exterior Orientation Parameters				
X_0	Y_0	Z_0	0.02 m	2.5×10^3
w	φ	κ	0.1 rad	1.0×10^2
Approx.	Object	Coordinates		
x	y		0.0005 m	4.0×10^6
	z		0.0008 m	1.5625×10^6
Image	Coordinates			
x	y		0.008 mm	1.5625×10^4

Note:
(1) Approximate values of exterior orientation parameters are obtained by using a metric ruler and a simple angle measuring device.
(2) Object coordinates are obtained for very close-range cases from coordinatograph data.
(3) Image coordinates are obtained at the Wild STK-1 stereocomparator.
(4) The standard error considered towards weights in this table are based on previous experience and realistic relative reliabilities.

Table 2. I.O. Parameters of the camera

Case n°	x0 (mm)	σx0 (mm)	y0 (mm)	σy0 (mm)	f (mm)	σf (mm)
1	-0.52	0.39	1.02	0.39	113.99	0.76
2	0.04	0.09	-0.59	0.62	84.63	0.91
3	0.03	0.13	-0.46	0.56	82.95	0.49
4	-0.02	0.26	-0.37	0.65	80.90	0.28

Note: Cases 1, 2, 3 and 4 correspond to 0.25 m, 1.0 m, 2.5 m, and 7.0 m, object distances, respectively.

Table 3. Lens Distortion Parameters of the Camera

	k_1	k_2	k_3	P_1	P_2	P_3
1	3.907	0.006	0.000	0.000	0.000	0.000
2	3.121	0.003	0.000	-0.128	-0.079	0.000
3	0.278	0.000	0.000	-0.025	0.000	0.000
4	0.109	0.000	0.000	-0.002	0.000	0.000

Note: 1, 2, 3 and 4 are the cases for 0.25 m, 1.0 m, 2.5 m, and 7.0 m, object distances, respectively.

Table 4. Accuracy Outputs for the Camera case 2

Instance	σ2	σf (mm)	σx (μm)	σy (μm)	σX (mm)	σY (mm)	σZ (mm)
i	2.02	1.18	13.4	11.6	0.04	0.04	0.09
ii	1.54	0.91	10.2	10.2	0.04	0.04	0.07
iii	1.54	0.91	10.2	10.2	0.04	0.04	0.07
iv	2.02	1.18	13.4	11.6	0.04	0.04	0.09

Note: σ^2: The estimated variance of unit weight.
σ_f: Standard deviation of the calibrated focal length.
σ_x and σ_y: Standard deviations of image coordinates.
σ_X, σ_Y, σ_Z: Standard deviations of adjusted object coordinates.

Table 5. Results of Relative Orientation (independent Method)

Photo	rotations/(standards deviations)			Py (average)	σ	Comments
	ω (gra)	φ (gra)	χ (gra)	(μm)	(μm)	
1	38.859 (0.019)	-2.097 (0.019)	3.077 (0.112)	8.5	3.5	No lens distortions considered
2	-37.315 (0.025)	1.891 (0.019)	3.069 (0.102)			
1	36.858 (0.019)	-2.106 (0.019)	3.636 (0.111)	5.4	2.4	Lens distortions considered
2	-37.431 (0.025)	1.891 (0.019	3.587 (0.102)			

Note: Here Py is the average residual y parallex after relative orientation; and σ is the normalized standard deviation of unit weight in the least-squares adjustment for orientation.

Table 6. Calibration Results for Diffrent Number of Photos

Object Dist.	N° of photos	σx0 (mm)	σy0 (mm)	f (mm)	σf (mm)	σx (μm)	σy (μm)	σx (mm)	σy (mm)	σz (mm)
0.25 m	4	0.39	0.39	113.99	0.76	6.5	8.4	0.02	0.02	0.07
	3	0.49	0.49	13.99	0.82	6.5	8.7	0.02	0.02	0.08
	2	0.61	0.65	3.96	0.90	7.0	8.8	0.03	0.03	0.08
1.0 m	4	0.09	0.62	84.63	0.91	10.2	10.2	0.04	0.04	0.07
	3	0.10	0.60	84.71	0.91	10.1	10.1	0.04	0.04	0.07
	2	0.13	0.65	84.61	1.00	10.1	10.5	0.04	0.04	0.08
2.5 m	4	0.13	0.56	82.95	0.49	7.0	10.6	0.03	0.03	0.06
	3	0.15	0.58	82.99	0.52	7.1	11.2	0.03	0.03	0.06
	2	0.18	0.60	82.78	0.54	7.1	11.5	0.03	0.03	0.06
7.0 m	4	0.26	0.65	80.90	0.28	5.0	13.4	0.10	0.10	0.13
	3	0.31	0.66	80.90	0.30	5.3	13.5	0.10	0.10	0.14
	2	0.38	0.70	80.75	0.35	5.4	14.0	0.11	0.11	0.14

Note: σx0 and σy0 are standard deviations of principal point coordinates. For the rest, see Note for Table 4.

Fig. 1

GEOMETRY OF THE PHOTOGRAPHY

Note: 1,2,3 and 4 are the camera stations; Object distances to the center of test area (S) are: 0.25 m, 1.0 m, 2.5 m and 7.0 m.

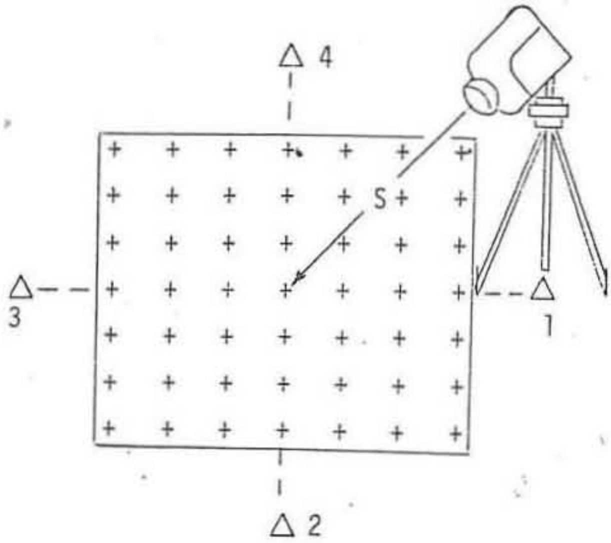
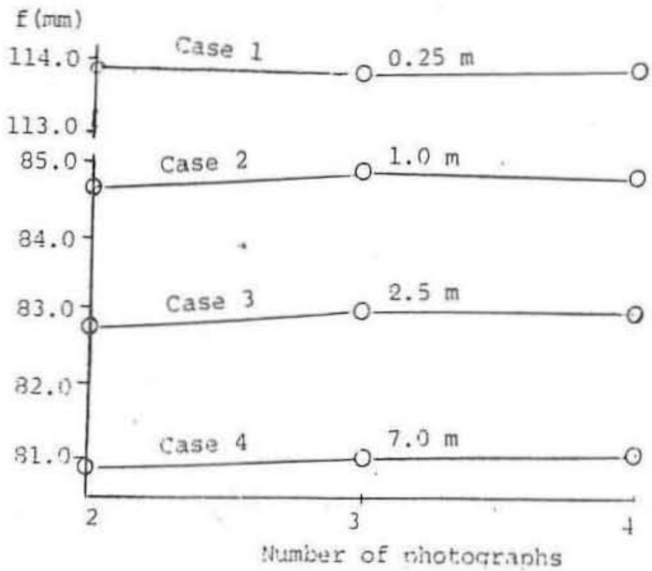


Fig. 2

FOCAL LENGTHS FOR VARIOUS OBJECT DISTANCES



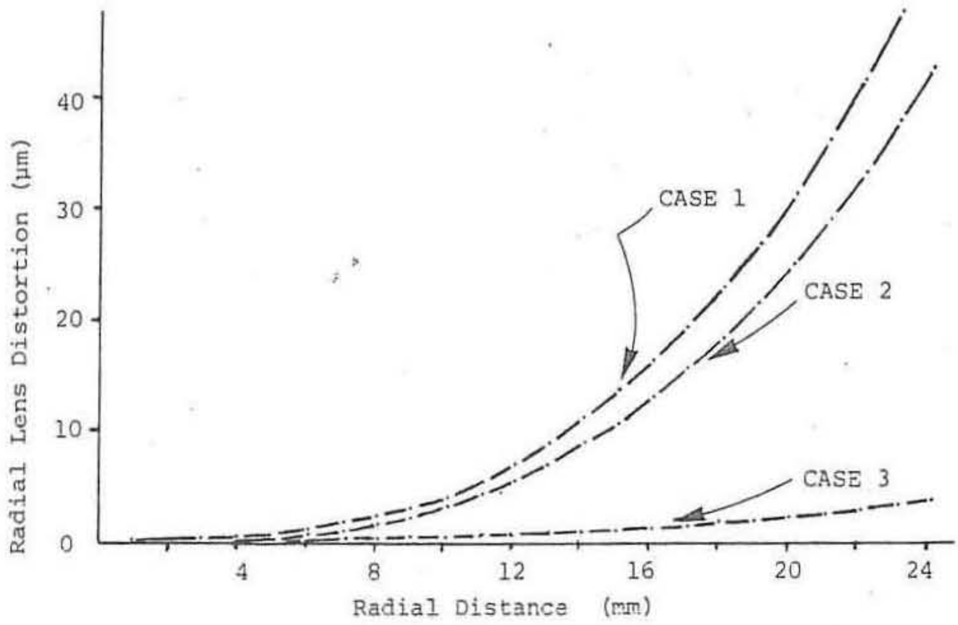


Fig. 3 : RADIAL LENS DISTORTION

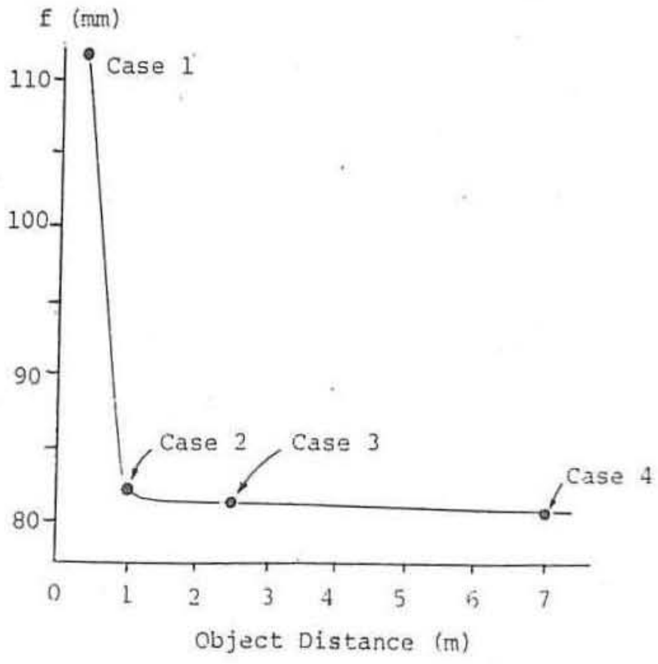


Fig. 4

CALIBRATED FOCAL LENGTHS