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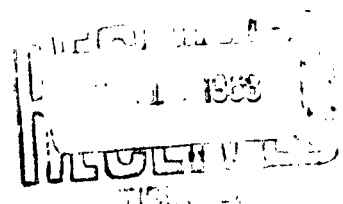
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**CALIBRATION OF PC-1000 CAMERAS
BY MEANS OF STAR PHOTOGRAPHY**

Myron W. Lawrence



RDT & E Project No. 1M222901A215

BALLISTIC RESEARCH LABORATORIES

ABERDEEN PROVING GROUND, MARYLAND

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BALLISTIC RESEARCH LABORATORIES

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Ballistic Measurements Laboratory

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MWLawrence/mec
Aberdeen Proving Ground, Md.
April 1963

CALIBRATION OF PC-1000 CAMERAS BY MEANS OF STAR PHOTOGRAPHY

ABSTRACT

Calibration of three PC-1000 cameras was performed utilizing approximate zenith exposures of stars. The calibration consists of determining the focal length, principal point, and lens distortion of each camera and corresponding estimates of precision derived from a rigorous least squares solution. Field work and data reduction procedures are described. Graphical presentation of lens distortion and a discussion of the results are included.

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1. INTRODUCTION

1.1 The determination of position by means of artificial satellites is one basic objective of geodetic satellite projects. The accuracy requirement for such a project necessitates determining satellite positions to within a few meters. In order to obtain these positions by ground based cameras, directions to the satellite must be measured accurately to a few seconds of arc.

The purpose of the calibration described in this report was to determine the metric qualities of three specific cameras contemplated for use with project ANNA (DOD Geodetic Satellite Project). The calibration included determining the focal length, the principal point, and lens distortion of each camera utilizing zenith exposure of stars. Furthermore, the residuals of the corresponding least squares solutions were used for determining the amount of tangential lens distortion which, if present, will affect the precision of direction measurements.

1.2 In November 1961, three PC-1000 cameras (Fig. 1) Nos. 103, 104, and 109 were made available on a temporary loan basis from the Orlando Air Force Base, Florida. Electronic timing devices and other auxiliary equipment for coding star trails accompanied the cameras. Air Force personnel, familiar with the system, participated in the field work to insure acquisition of the necessary plates and related timing records.

Field work consisted of collecting a series of zenith star exposures using the PC-1000 cameras. Coding of star trail images was accomplished by the use of two types of shutters. Plates were measured on the STK-1 No. 818 Wild Stereocomparator and reduced by appropriate computer programs. Graphical presentations of the lens distortions and a brief discussion of the results are included.

2. FIELD INSTRUMENTATION AND PROCEDURES

2.1 PC-1000 Camera and Components

The PC-1000 camera features a 1000 millimeter $f/5$ lens. The plate size is 190 x 215 x 6 millimeters, with a usable field of about 170 x 170 millimeters. Plates used were flat to approximately 6 fringes and were coated with Eastman



FIG. 1
PC-1000 CAMERA

Kodak Spectroscopic type 103-F emulsion. The lens elements were aligned and assembled with a between-the-lens type shutter (internal shutter) in a camera housing by the Instrument Corporation of Florida. An in-front-of-the-lens shutter (capping shutter), manufactured by the Fred C. Henson Company of Pasadena, California and furnished by BRL was also used for the calibration. While using the capping shutter (Fig. 2) the internal shutter was kept open and vice-versa. All exposures were made using a maximum aperture and a clear filter.

2.2 Internal Shutter

When using the internal shutter, the exposure times were programmed by a slotted rotating disk. The shutter was activated by a light beam directed at the rotating slotted disk, which contained six slots of different lengths. When the disk rotated, the light beam passed through these slots energizing a photoelectric cell which was positioned opposite the light source. The resulting signal activated a circuit, which in turn opened the shutter. When the disk had rotated so that the light was again blocked off, the shutter closed. The length of the slot therefore controlled the length of the exposure and consequently the length of the star trail on the plate. The duration of the exposures given by the six slotted openings were approximately 4, 2, 1, $1/2$, $1/4$ and $1/8$ seconds, with a lapse of about fifteen seconds between slots. The opening and closing times of the shutter were recorded on magnetic tape, together with corresponding one-per-second WWV time signals. The magnetic tape was then played back and recorded on Brush Recorder paper, where the exposure time could be visibly correlated with the WWV signal. Since radio reception was unreliable, the time signal was often submerged in the noise of the record. This made it difficult to define the times of the star trails when interpolating between WWV second pips. The entire program was repeated three times to insure that a sufficient number of star trails would be produced by this shutter. The time between runs was approximately two minutes. After the plate was developed the trails of different lengths were studied and it was decided that trails produced by the $1/4$ second slot could be best utilized.

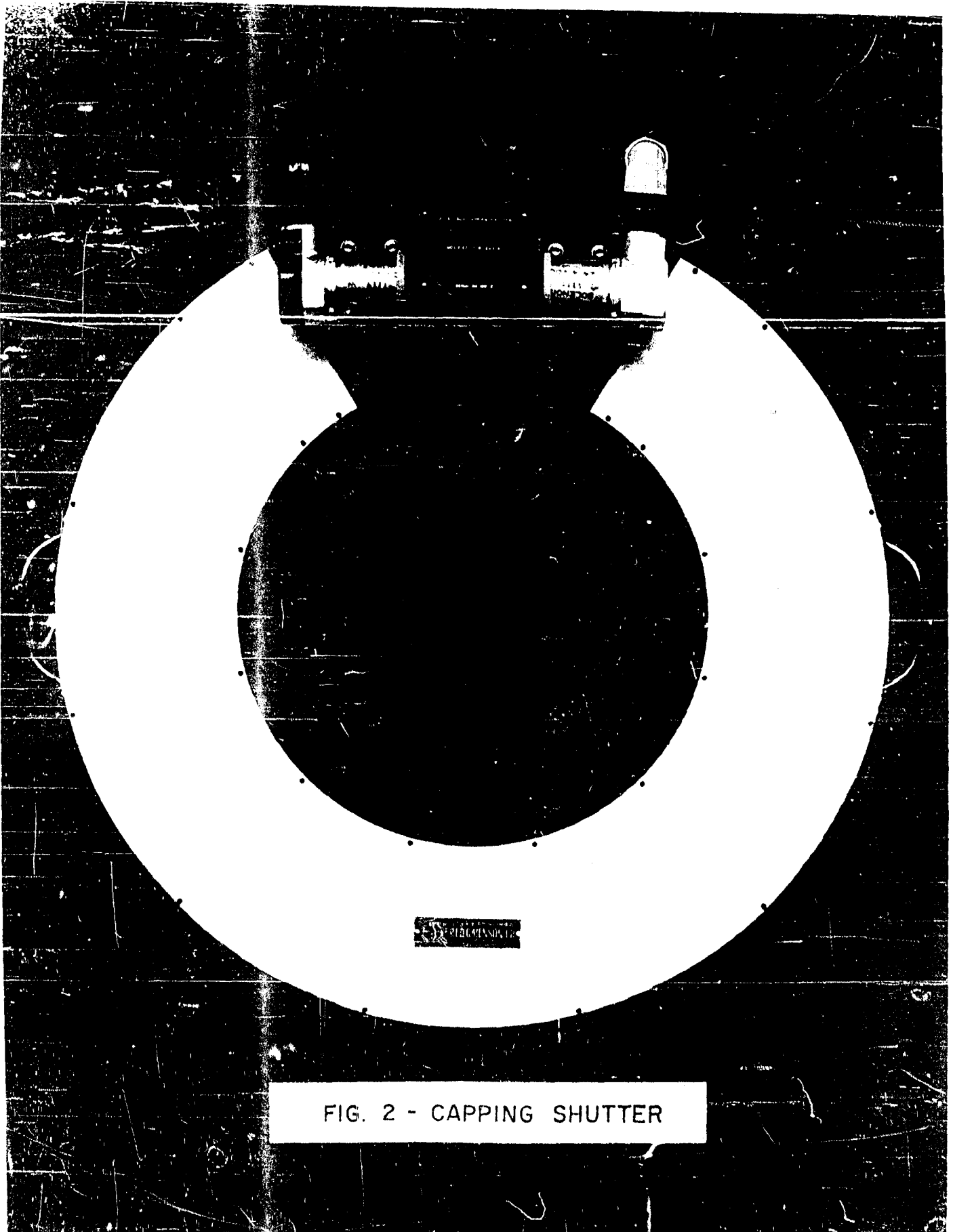


FIG. 2 - CAPPING SHUTTER

2.3 Capping Shutter

The capping shutter was activated by a one-per-second frequency standard pulse which had been previously synchronized with WWV. Therefore, the reception difficulty encountered while using the internal shutter was nonexistent. The opening and closing times of the shutter were adjusted so as to occur within one millisecond on the second. The shutter program and the pulse from the frequency standard were recorded simultaneously on Brush Recorder paper in order to facilitate analysis during data reduction. The shutter program used was: open five seconds -- closed one second -- repeated six times. This pattern permitted five images to be measured by setting the measuring mark between the corresponding star images. Since a line is more easily detected on a plate than a short dash or dot, images produced while using the capping shutter were more suited for the purpose than images produced with the internal shutter. In addition, the time-coded star trails obtained by the capping shutter aided in locating many of the images produced by the internal shutter that otherwise might not have been identifiable. Table 1 is a summary of the numbers of stars which were measured and used in the calibration.

TABLE 1

	<u>NUMBER OF STARS MEASURED AND USED</u>					
	Camera 103		Camera 104		Camera 109	
	Measured	Used	Measured	Used	Measured	Used
Capping Shutter	55	46	113	102	88	75
Internal Shutter	20	17	35	32	25	19

NOTE: Some of the stars that were measured were not used in the calibration because of marginal image quality.

2.4 Temperature, Pressure, Humidity

Temperature, pressure, and humidity readings were taken during the time the plate was being exposed. These values were then used in the computation of refraction corrections for the star positions.

2.5 Camera Orientation

The three cameras were oriented approximately at zero degree zenith distance.

3. REDUCTIONS

3.1 Plate Measurements

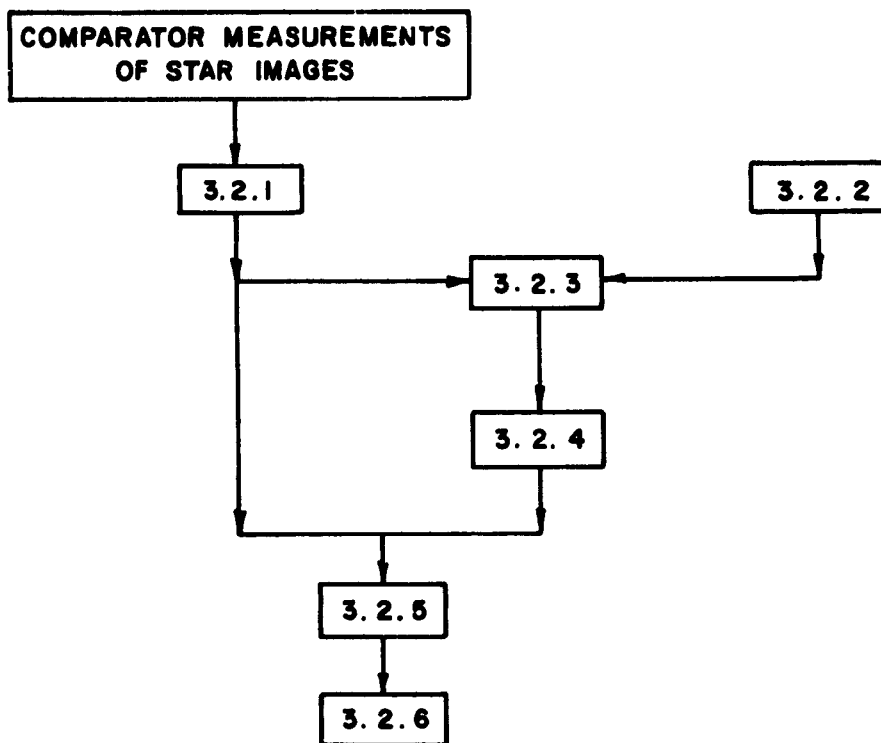
For each plate, a duplicate negative was made which served as the work plate on which unidentified and identified stars were marked and numbered for the measuring program. This procedure minimized the possibility of damaging the original plate. The identified stars were used to determine a preliminary camera orientation which then was used to identify all the stars selected for the calibration. During the measuring process, the duplicate plate was placed on the right (px and py) side of the stereocomparator and the original plate on the left (x and y) side. By properly utilizing the swing and px-py motions of the stereocomparator, the operator viewed the marked stars with the right ocular and proceeded to measure the stars on the original plate as viewed with the left ocular. Fiducial marks were measured in addition to the stars in order to define a convenient reference system for determining the coordinates of the principal point. These measurements also allow scale corrections for emulsion shrinkage to be made, based on the calibrated distances between fiducial marks.

3.2 Sequence of Data Reductions

For each camera calibration, the following sequence of steps was followed:

- 3.2.1 Comparator Reduction Program
- 3.2.2 Preliminary Star Identification and Star Reduction Program
- 3.2.3 Preliminary Camera Orientation Program
- 3.2.4 Star Identification and Reduction Program
- 3.2.5 Camera Orientation Program
- 3.2.6 Plotting Program

The following flow diagram indicates the sequence of reductions.



3.2.1 Comparator Reduction Program [1]*

The essential steps in the comparator program are:

- (a) correct any systematic comparator errors

* See references at end of report.

- (b) form arithmetic averages for multiple settings of star measurements and if desired -

compute weight factors from the random discrepancies present in each set of measurements,

or compute weight factors as a function of the angle of incidence,

or introduce weights determined a priori.

- (c) reduce all plate measurements to an origin as defined by the intersection of two lines joining the two pairs of opposite fiducial marks
- (d) rotate the comparator coordinate system until it is parallel to a specific set of fiducial marks
- (e) shift the origin to the principal point if x_p and y_p are known
- (f) apply lens distortion corrections

NOTE: Only steps (a) through (d) are required for a camera calibration.

3.2.2 Preliminary Star Identification and Star Reduction Program

Right ascension and declination of the center of the plate are derived from the azimuth, zenith distance and instant of exposure by means of formulas from Chauvenet's Spherical Trigonometry. Utilizing these computed values, together with appropriate star charts, several of the brightest stars on the exposed plate can be readily identified. Right ascensions and declinations for these stars are obtained from a star catalogue and used in the Star Reduction Program [2] to obtain standard coordinates.

3.2.3 Preliminary Camera Orientation Program [3]

The purpose of this program is to obtain good approximate values for the camera orientation elements α , ω , κ , c , x_p and y_p . (The orientation elements are defined in Section 3.2.5). Input for this program consists of standard coordinates and plate coordinates of the preliminary stars together with approximate values of α , ω , and κ , as computed from Formula 8 of [4].

3.2.4 Star Identification and Reduction Program [2]

The Star Identification Program uses orientation elements obtained from the Preliminary Camera Orientation Program and plate coordinates from the Comparator Reduction Program to obtain approximate right ascensions and declinations of the unidentified stars. Each star is identified in the program by comparing this approximate right ascension and declination with corresponding values in a star catalogue, (the AGK₃ Catalogue was used for the three PC-1000 camera calibrations).

The standard coordinates for each star are then computed using the catalogue values.

3.2.5 Camera Orientation Program [3]

The Input* for this program consists of the standard coordinates from the Star Reduction Program (3.2.4), and corresponding plate coordinates as obtained from the Comparator Reduction Program (3.2.1).

The Output* consists of the orientation elements α, ω, κ and the required calibration parameters $c, x_p, y_p, K_0, K_1, K_2, K_3$ where:

α, ω, κ are three rotation parameters

c is the adjusted focal length

x_p and y_p are the coordinates of the principal point, and

K_0, K_1, K_2 and K_3 are distortion coefficients used to compute radial distortion as:

$$\Delta = K_0 r + K_1 r^3 + K_2 r^5 + K_3 r^7; \text{ (}\Delta \text{ is the amount of radial distortion and } r \text{ is the radial distance from the principal point)}$$

* linear parameters are given in meters.

3.2.6 Plotting Program

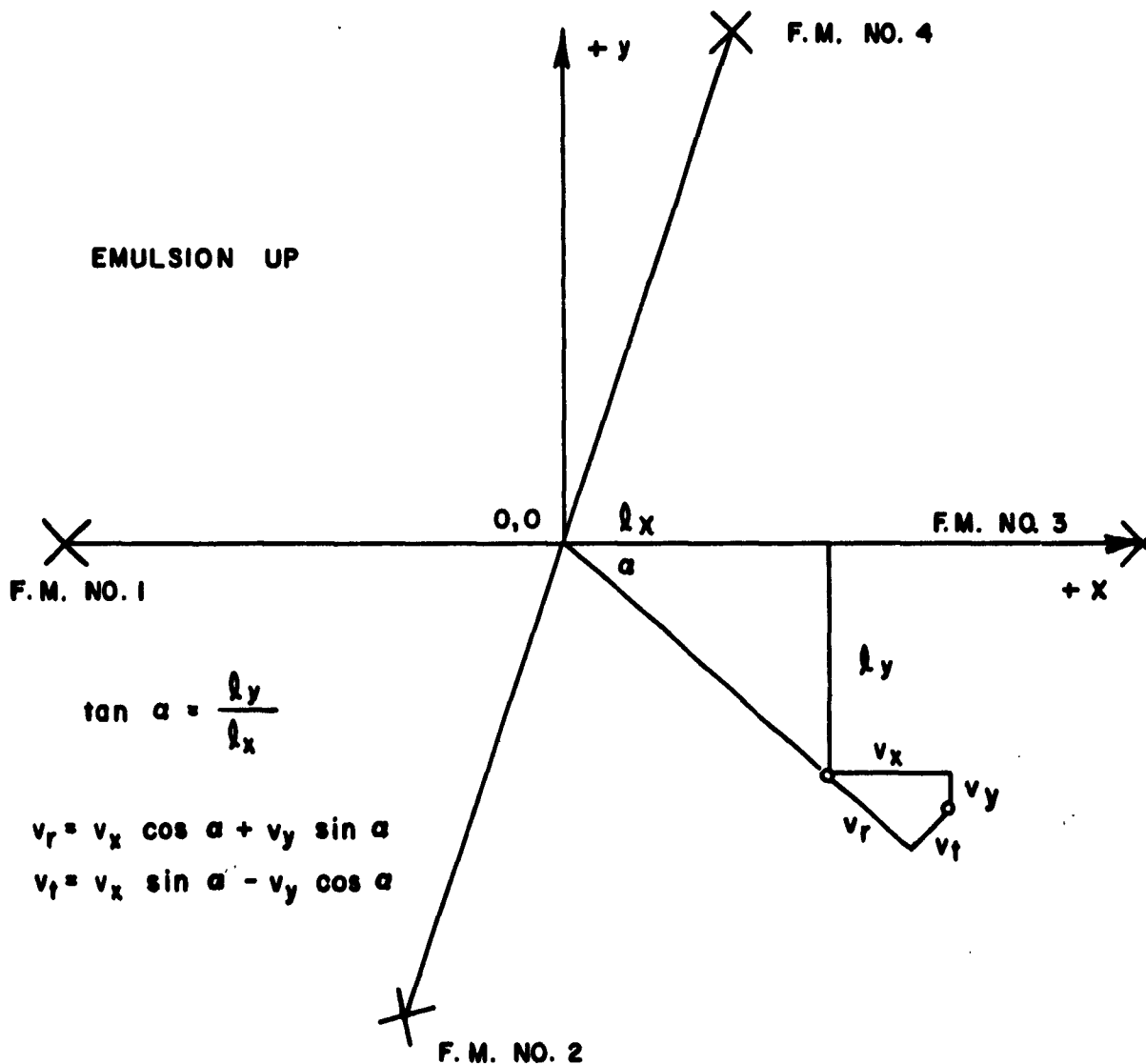
The purpose of this program is to compute radial and tangential distortion residuals (v_r and v_t) and to present these values in a graphical form (see Fig. 3).

Input values for the program consist of the plate coordinates (ℓ_x and ℓ_y) of each star as obtained from the Comparator Reduction Program, the residual errors of these plate coordinate (v_x and v_y) and the coordinates of the principal point (x_p and y_p) as obtained by a least squares solution from the Camera Orientation Program. The v_x and v_y values are converted into v_r and v_t values and scaled up by a predetermined scale factor to insure a suitable graphical presentation. The origin of the plot is translated to the principal point by introducing the corresponding x_p and y_p values.

Results of the Plotting Program are shown in Figs. 4A through 4C, which present radial and tangential distortion values as obtained for the three PC-1000 cameras. These values include measuring errors corresponding to a standard deviation of approximately 8 microns.

4. DIRECTION PROGRAM

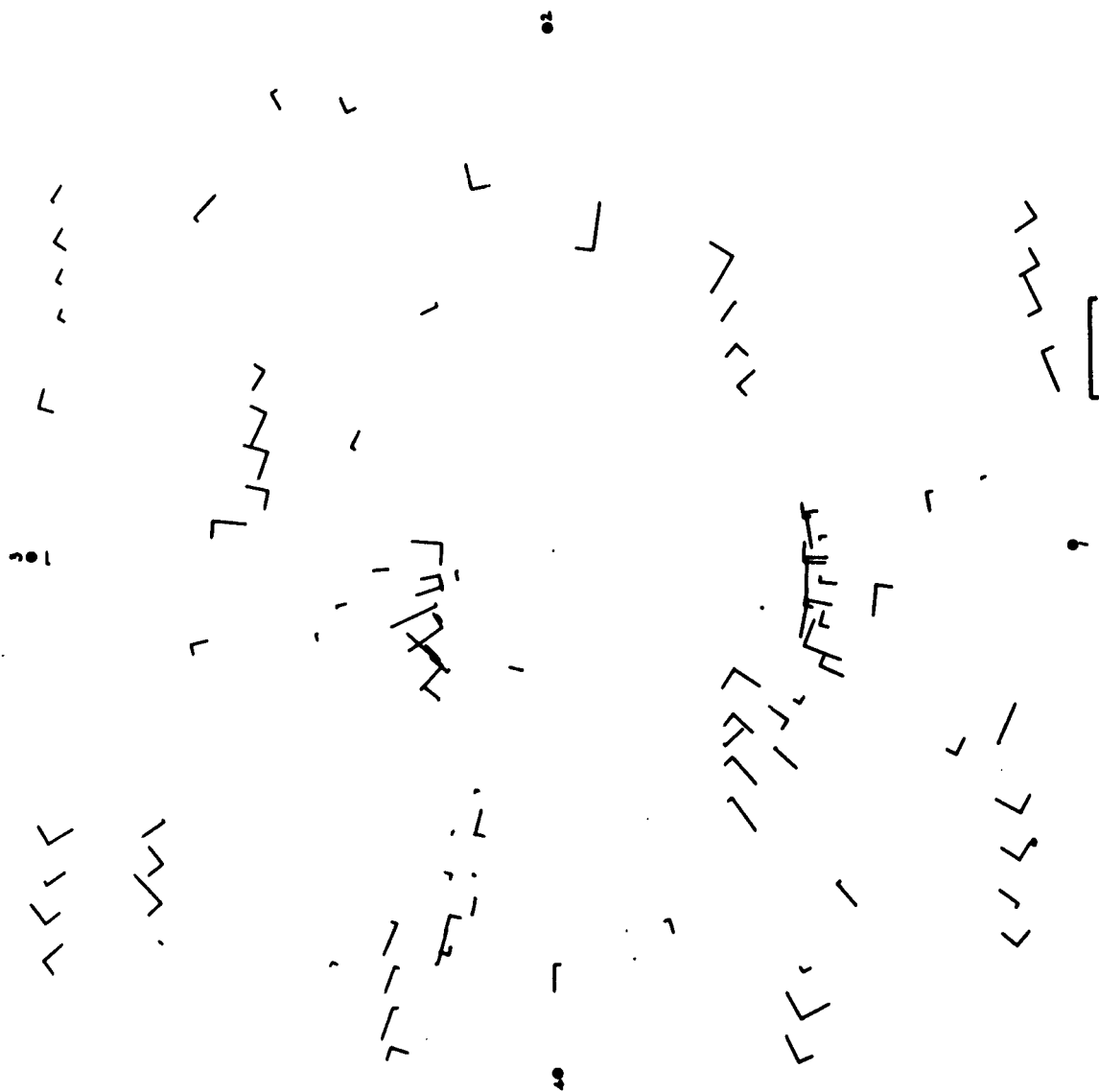
An investigation was made concerning the influence of the two types of shutters used upon the metric quality of the corresponding photographic record. This required the computing of two camera orientations, using only the stars imaged by each shutter. Based on these results, and applying formulas and procedures similar to those used in 3.6 of [5], directions were computed for two fictitious points corresponding to the center and a corner of the plate. Results as tabulated in Table 2 show that the differences in directions produced by the two shutters were small.



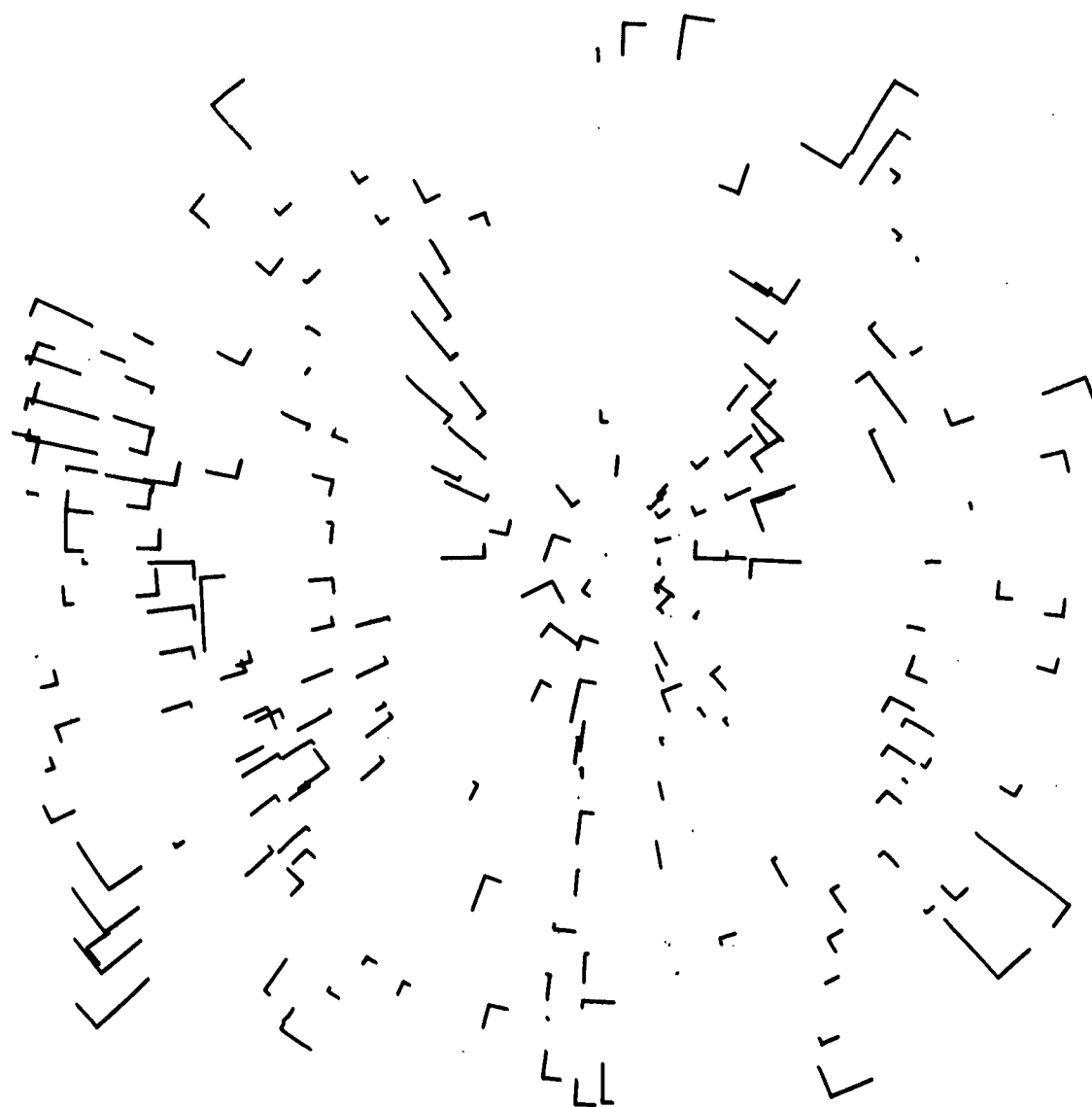
Where

l_x l_y ARE PLATE COORDINATES OF STAR
 v_x v_y ARE RESIDUALS IN THE PLATE COORDINATES
 v_r v_t ARE THE CORRESPONDING RADIAL AND TANGENTIAL
DISTORTION COMPONENTS

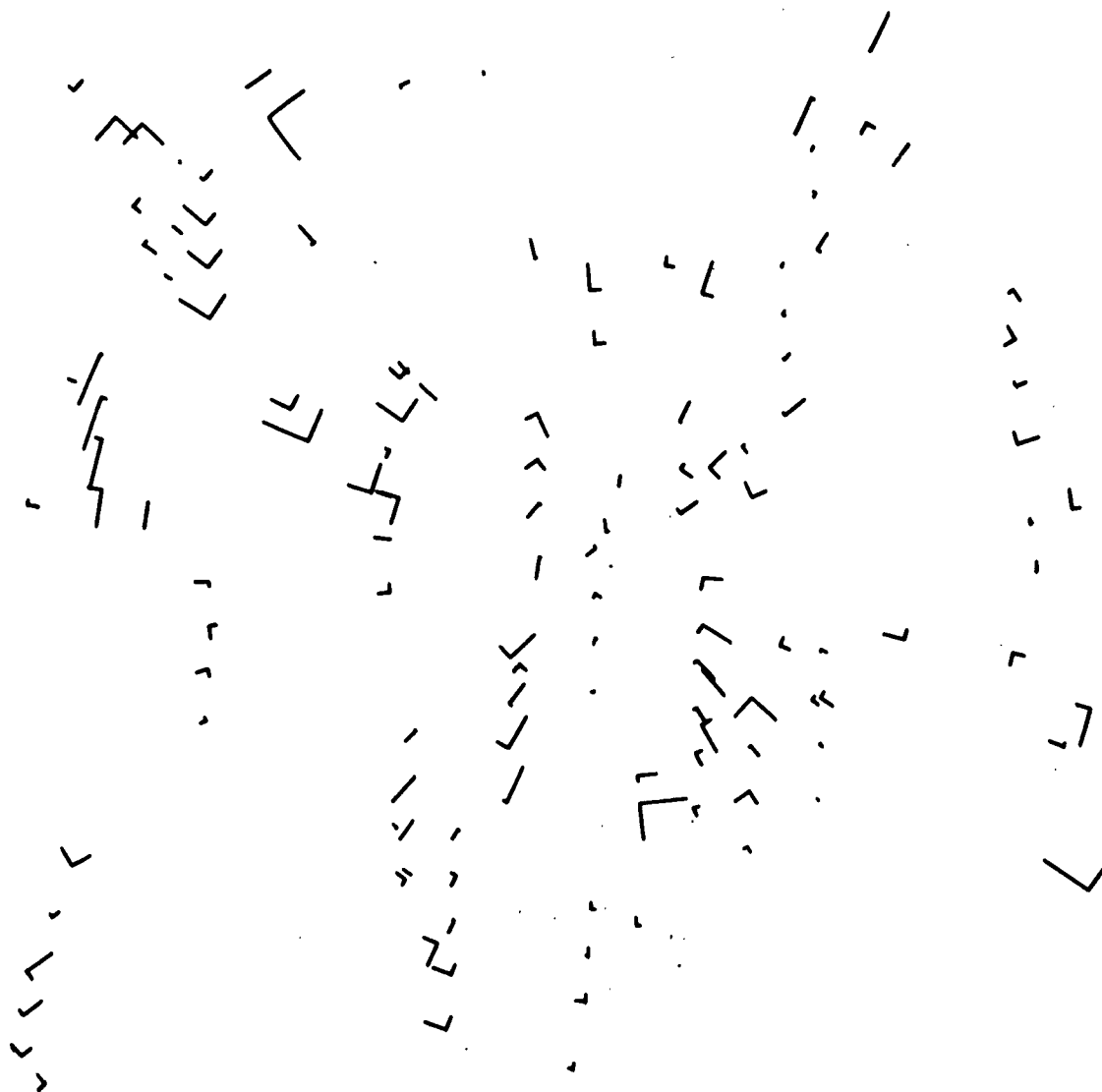
FIG. 3 - PLOTTING PROGRAM



50 MICRONS
FIG. 4A
 RADIAL AND TANGENTIAL DISTORTION
 PC-1000 NO. 103



50 MICRONS
FIG. 4B
 RADIAL AND TANGENTIAL DISTORTION



50 MICRONS

FIG. 4C

RADIAL AND TANGENTIAL DISTORTION

PC-1000 NO. 109

TABLE 2

RESULTS OF DIRECTION PROGRAM

Center of Plate $l_x = l_y = 0$		Corner of Plate $l_x = l_y = .065$ meters
CAMERA 103		
$\Delta''\delta$	+1.00	+1.01
$(\Delta''\alpha)(\cos \delta)$	-0.35	-1.04
CAMERA 104		
$\Delta''\delta$	+0.37	+0.67
$(\Delta''\alpha)(\cos \delta)$	-0.70	-1.05
CAMERA 109		
$\Delta''\delta$	+0.16	-0.14
$(\Delta''\alpha)(\cos \delta)$	-1.16	+0.70

$\Delta''\delta$ is the difference in declination and

$\Delta''\alpha$ is the difference in right ascension as obtained by the two types of shutters.

5. CALIBRATION RESULTS

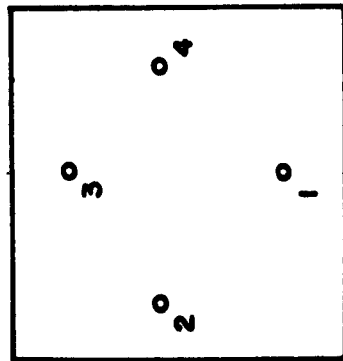
The results of the calibrations are shown in Table 3 and Figs. 5 through 11. The one sigma error level of the distortion curves shown in Figs. 7, 9, and 11 resulted from the fact that a crossover point of .065 meters was enforced.

	TABLE 3						
	<u>Camera 103</u> ⁽¹⁾			<u>Camera 104</u> ⁽²⁾	<u>Camera 109</u> ⁽²⁾		
c*	+.10143219	+01		+.10213468	+01	+.10164131	+01
x _p	+.11227386	-02		+.37157433	-02	+.38252082	-02
y _p	-.48750155	-03		-.31050232	-02	-.42985370	-02
c	+.10145372	+01		+.10216897	+01	+.10165417	+01
K ₀	-.21230287	-03		-.33579670	-03	-.12652302	-03
K ₁	+.81546644	-01		+.73673675	-01	+.68225669	-02
K ₂	-.95307218	+01		+.17542068	+01	+.74248385	+01
K ₃	+.50249533	+03		-.90007479	+02	-.46195770	+03

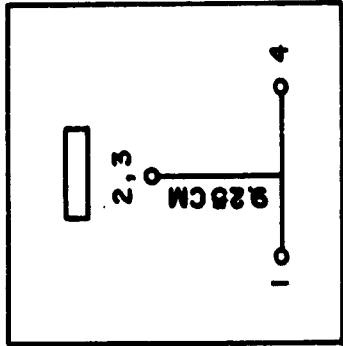
Linear parameters are given in meters, c is the calibrated focal length corresponding to a cross-over point of the distortion curve of .065 meters.

(1) In the case of camera 103, the principal point was referred to the intersection of the two lines joining opposite pairs of fiducial marks.

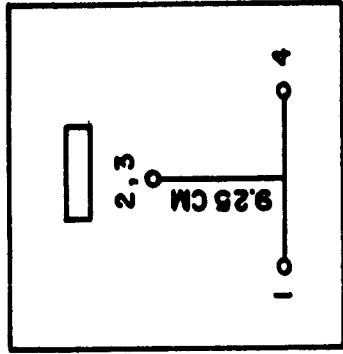
(2) In the case of cameras 104 and 109, the dark slide was not completely pulled when the plates were exposed; as a result fiducial marks 2 and 3 were not imaged. Therefore, the principal point was referred to a point on the perpendicular bisector and at a distance of 9.25cm from line 1-4. Coordinates of the fiducial marks are also given for scale corrections (see Fig. 5).



CAMERA 103



CAMERA 104



CAMERA 109

NEGATIVE PLATES EMULSION DOWN

PT.	X	Y	X	Y	X	Y
1	-.86808943 -01	0	-.12081454 +00	0	-.12084688 +00	0
2	-.30048607 -.03	-.87611741 -01	0	0	0	0
3	+.87089469 -.01	0	0	0	0	0
4	+.29950413 -.03	+.87324246 -01	-.20833257 -01	+.11900177 +00	-.20763194 -01	+.11904790 +00
P.P.	+.11227386 -.02	-.48750155 -03	+.37157433 -.02	-.31050232 -.02	+.38252082 -.02	-.42985370 -.02

FIG. 5
COORDINATES OF FIDUCIAL MARKS & PRINCIPAL POINT (METERS)

FIG. 6
HISTOGRAM AND NORMAL DISTRIBUTION CURVE OF RESIDUAL
ERRORS OF THE PLATE MEASUREMENTS
PC-1000 NO. 103

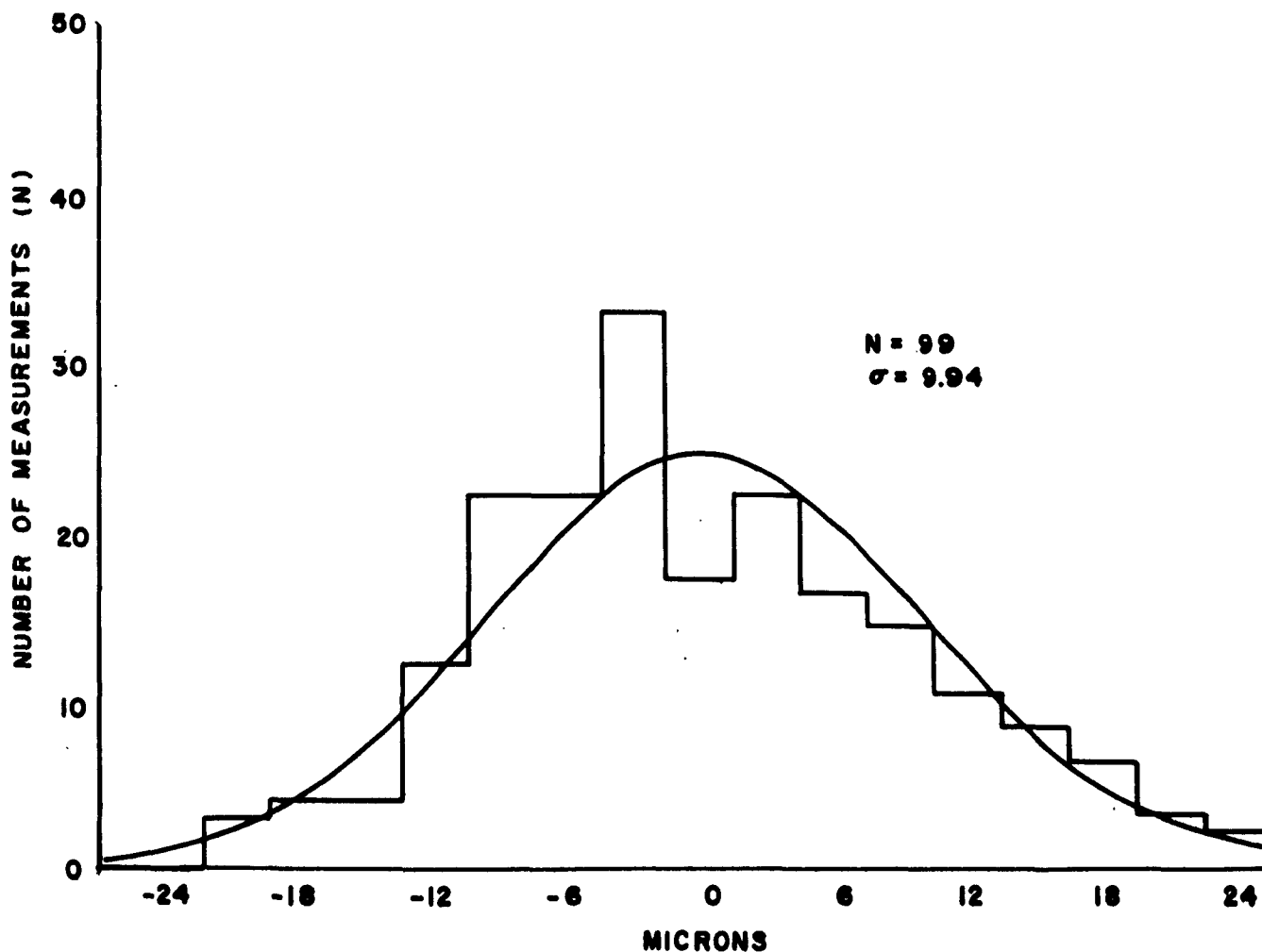


FIG. 7
DISTORTION CURVE
PC-1000 NO. 103

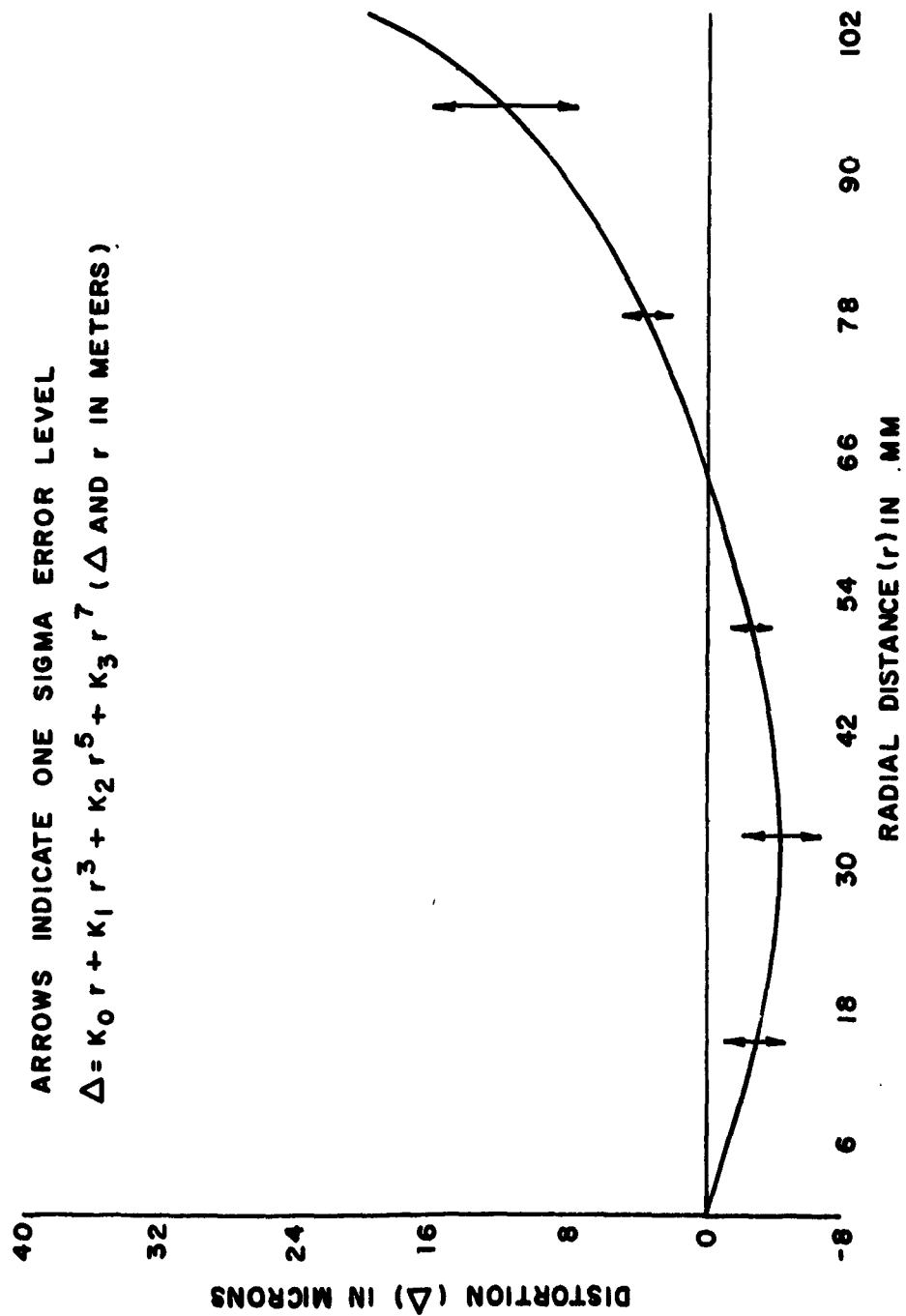


FIG. 8
HISTOGRAM AND NORMAL DISTRIBUTION CURVE OF RESIDUAL ERRORS
OF THE PLATE MEASUREMENTS
PC-1000 NO.104

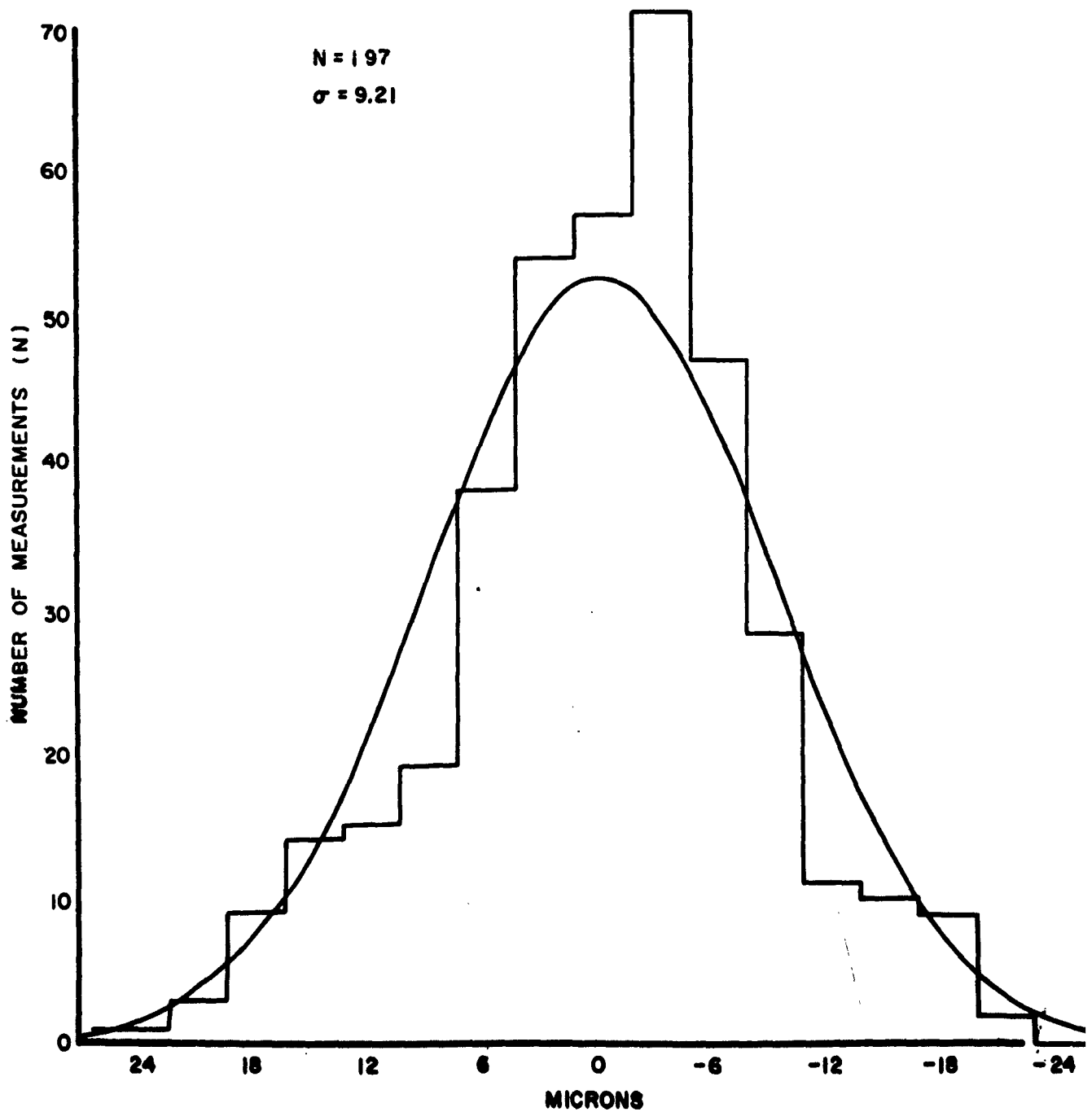


FIG. 9
DISTORTION CURVE
PC-1000 NO. 104

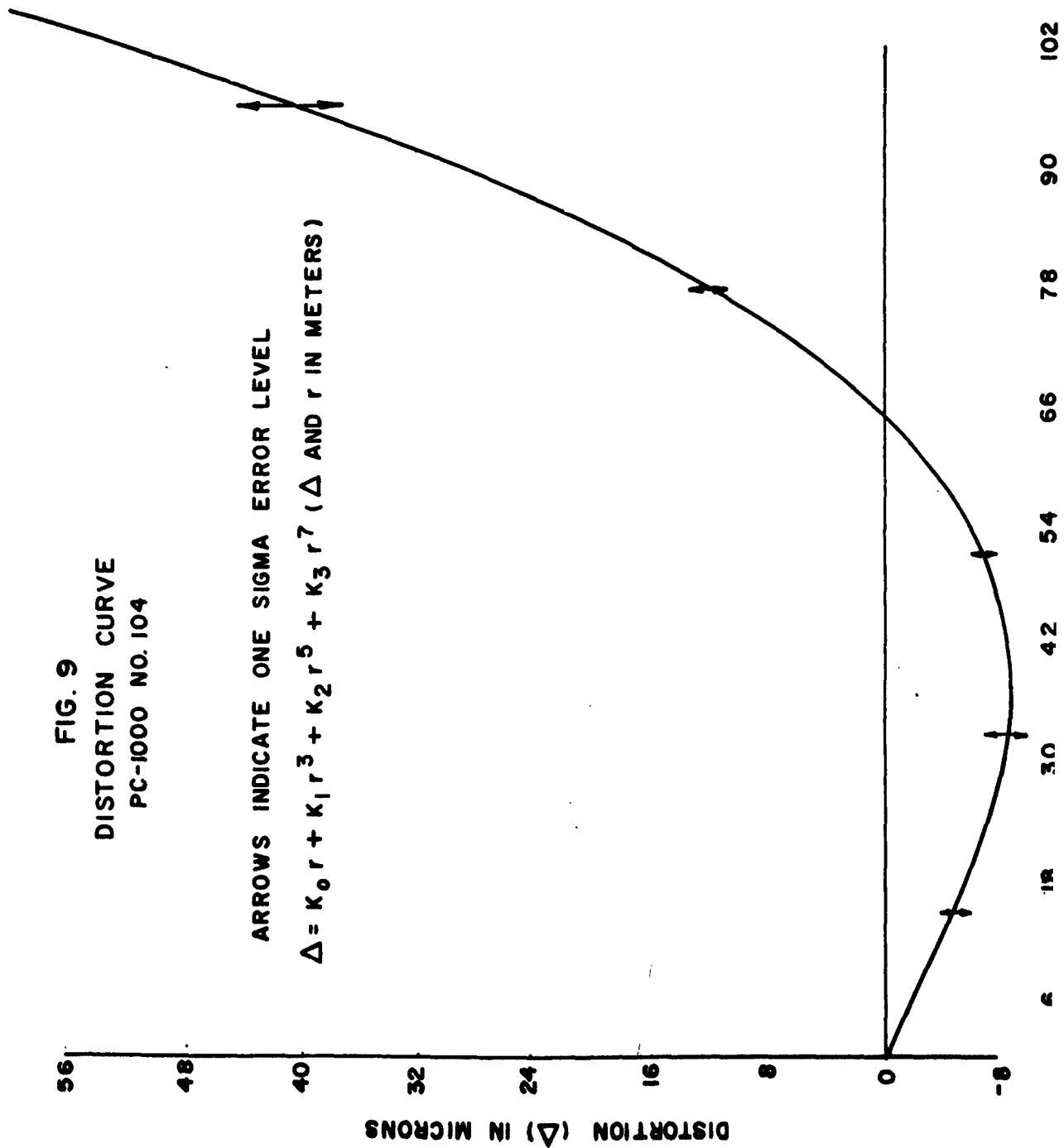


FIG. 10
HISTOGRAM AND NORMAL DISTRIBUTION CURVE OF RESIDUAL
ERRORS OF THE PLATE MEASUREMENTS
PC-1000 NO. 109

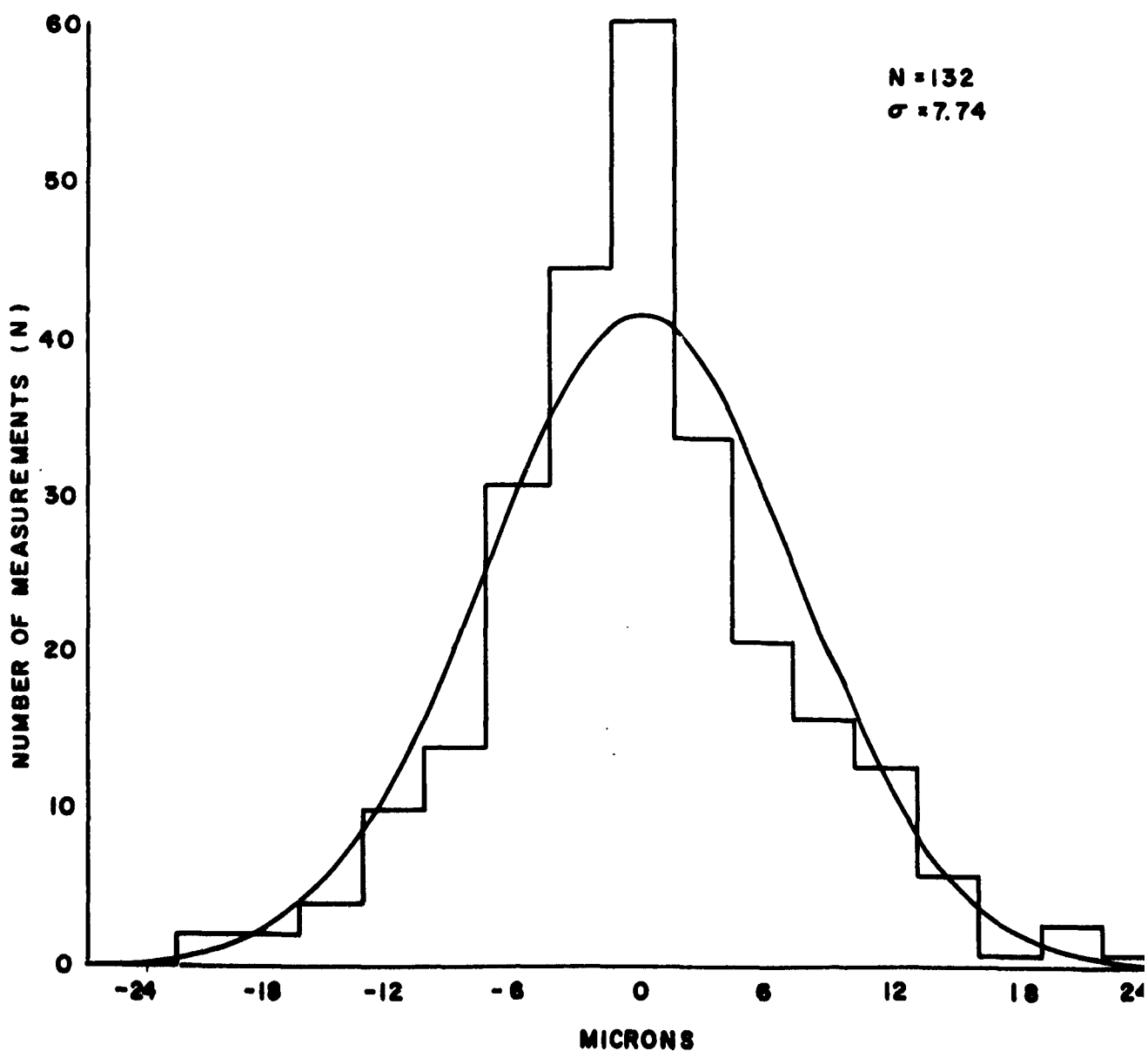
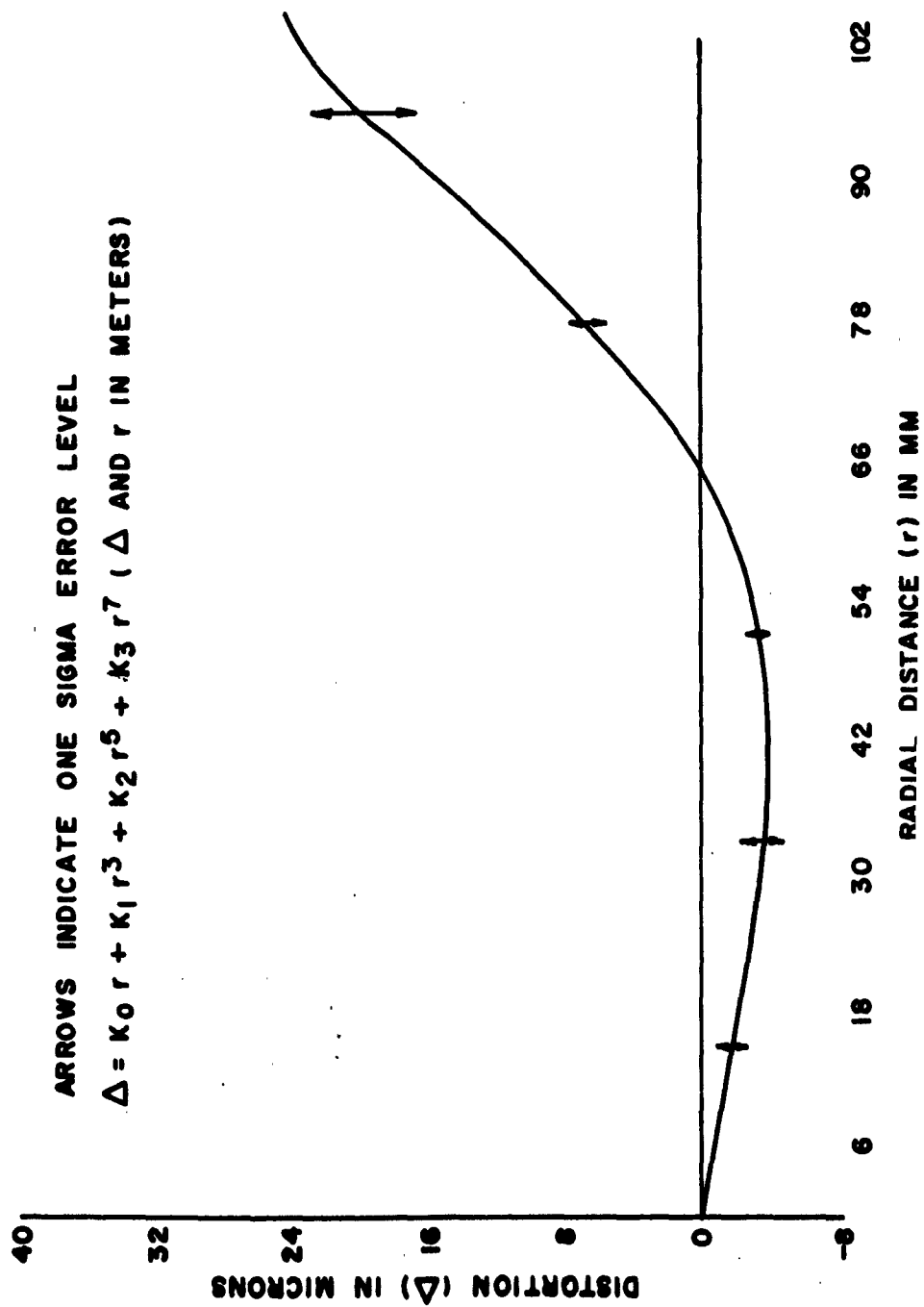


FIG. 11
DISTORTION CURVE
PC-1000 NO.109



6. CONCLUSIONS

As expected from a lens with a small angle of view (10°), the radial distortion characteristics of the PC-1000 cameras are adequate to meet most precision measurement requirements. However, the presence of large amounts of tangential distortion as shown by Figs. 4A to 4C has the effect of limiting the camera as a precision measuring instrument.

The significance of the calibration results, given in Section 5, is especially impaired because of the relatively small number of star images produced by the PC-1000 camera. A large number of star images distributed evenly over the plate is required to interpret significantly the proven distortion asymmetries. To insure required star density for the PC-1000 cameras, a star must be imaged on a plate several times. Such an operation, however, would require a camera mount of exceptionally high stability.

Myron W. Lawrence
MYRON W. LAWRENCE

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