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PHOTOGRAMMETRIC CALIBRATION OF THE NASA-WALLOPS ISLAND IMAGE INTENSIFIER SYSTEM

Prepared For

National Aeronautical and Space Administration
Wallops Station
Wallops Island, Virginia 23337

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1.0 INTRODUCTION

A Scout rocket was launched in October 1971 from the National Aeronautics and Space Administration (NASA) launching facility at Wallops Island, Virginia releasing a Bariom Ion Cloud (BIC) over Central America at an altitude of approximately 20,000 miles. The primary purpose of this experiment was to map the shape of both the cloud and the individual magnetic field lines as the Barium Ion Cloud expanded in the earth's magnetic field.

One of the primary tracking systems for the BIC Project, the Wallops Island Image Intensifier System, was designed and engineered by Electro-optical Systems (EOS), a subsidary of the Xerox Company of Pasadena, California. The Image Intensifier System, an electro-optical device capable of photographing low-light objects by electronically enhancing the light received from them, consists of f/1 objective lens, an image intensifier tube, and a relay lens. Two additional systems, an interference filter for the objective and a Flight Research Corporation Model 370 Multidata Camera were added at Wallops.

It was anticipated by Wallops personnel that two computer programming systems initially written by DBA Systems, Inc. for use at the Air Chart and Information Center (ACIC) in Saint Louis, Missouri, (1) A Definitive Stellar Camera Calibration program and (2) The Geodetic Stellar Camera Orientation program, could be used to calibrate the distortions of the Image Intensifier systems and for subsequent data reduction (i.e. determination of direction from the tracking station to a specific point on the cloud) of the BIC project photographs. However, when stellar calibrations were attempted using the symmetric radial and decentering distortion models, an rms error of photo residuals less than 100 micrometers could not be achieved. This clearly indicated that the image tube produced a significant level of unmodelled systematic error.

In September of 1971, DBA Systems, Inc. (DBA) received a contract from the National Aeronautics and Space Administration (NASA)/Wallops Station, to develop a mathematical model to define the Image Intensifier distortions and to implement this additional model in the programs identified above on the GE 625 computer at Wallops.

In this report we shall outline the development of a suitable mathematical procedure for determining the Image Intensifier distortions and the implementation of this model in the Wallops computer programs.

2.0 ANALYTICAL CALIBRATION OF METRIC CAMERAS

2.1 Introduction

A brief summary of the stellar method of calibration of symmetric radial and decentering lens distortion simultaneously with elements of interior orientation (x_p, y_p, c) and the exterior orientation angles (α, ω, κ), is given in this section.

2.2 Symmetric Radial Distortion

The stellar method of simultaneous calibration of symmetric radial distortion was developed by (Brown, 1956, 1957, 1964). This work exploited the result from optical ray tracing that the radial distortion δr of a perfectly centered lens can be expressed as an odd powered series of the form:

$$\delta r = K_1 r^3 + K_2 r^5 + K_3 r^7 + \ldots \tag{1}$$

in which,

$$r = (x^2 + y^2)^{\frac{1}{2}} = \text{radial distance}$$

x, y = coordinates of image referred to the principal point as origin.

Since x, y components of distortion can be expressed as:

$$\delta x = \frac{x}{r}\,\delta r \qquad \delta y = \frac{y}{r}\,\delta r \tag{2}$$

it was shown that coefficients of distortion $(K_1, K_2, K_3, \ldots)$ could be introduced directly into the projective equations and determined simultaneously with the elements of camera orientation in a rigorous least squares adjustment.

2.3 Decentering Distortion

Only recently has it become appreciated that results for virtually all metric cameras are compromised to a small but significant extent by decentering distortion (Brown, 1964). Decentering distortion is the result of imperfect centering of lens elements. In an earlier form of the Analytical Calibration program, the thin prism model was used to account for decentering distortion with satisfactory results. According to the thin prism model, a decentered lens is the equivalent of a perfectly centered lens in combination with a thin prism of appropriate deviation and orientation.

Subsequently (Brown, 1965) it was discovered that a mathematically rigorous model for decentering distortion had been developed by Conrady (1919) and that this model could be shown to be projectively equivalent to the thin prism model for first order effects but not for higher order effects. Accordingly, an extended form of the Conrady model has replaced the thin prism model in the Camera Calibration programs.

In terms of radial and tangential components, Conrady's model assumes the form:

$$\begin{aligned} \Delta r &= 3P_r \sin(\varphi - \varphi_0) \\ \Delta t &= P_r \cos(\varphi - \varphi_0) \end{aligned} \tag{3}$$

in which,

P_r = $J_1 r^2 + J_2 r^4 + J_3 r^6 + \ldots$ = profile function of tangential distortion

φ = angle between positive x axis and radius vector to point x,y

φ_0 = angle between positive x axis and axis of maximum tangential distortion.

In Brown (1965) it is shown that Conrady's model can be expressed in terms of x and y components as:

$$\Delta x = [P_1(r^2 + 2x^2) + 2P_2xy][1 + P_3r^2 + \ldots]$$
$$\Delta y = [2P_1xy + P_2(r^2 + 2y^2)][1 + P_3r^2 + \ldots] \qquad (4)$$

in which the new coefficients P_1, P_2, P_3, and P_4 are defined by:

$$\begin{aligned} P_1 &= -J_1 \sin\varphi_0 \\ P_2 &= J_2 \cos\varphi_0 \\ P_3 &= J_2/J_1 \\ P_4 &= J_3/J_1 \\ &\vdots \end{aligned} \qquad (5)$$

This formulation has the advantage of being a linear expression in the coefficients P_1, P_2 when the higher order coefficients P_3, P_4 are zero.

2.4 Observational Equations

The projective equations resulting from an undistorted central projection may be written as (Brown, 1957):

$$x - x_p = c\,\frac{A\lambda + B\mu + C\nu}{D\lambda + E\mu + F\nu}$$
$$y - y_p = c\,\frac{A'\lambda + B'\mu + C'\nu}{D\lambda + E\mu + F\nu} \qquad (6)$$

in which,

x_p, y_p, c = elements of interior orientation

λ, μ, ν = X, Y, Z direction cosines of ray joining corresponding image and object points

$$\begin{bmatrix} A & B & C \\ A' & B' & C' \\ D & E & F \end{bmatrix}$$ = orientation matrix, elements of which are functions of three independent angles $\alpha, \omega, \varkappa$ referred to arbitrary X, Y, Z frame in object space.

If we then let x^o, y^o represent the observed photo coordinates, the left hand sides of the projective equations (6) can be replaced by:

$$\begin{aligned} x - x_p &= \bar{x} + v_x + \bar{x}(K_1 r^2 + K_2 r^4 + K_3 r^6 + \ldots) \\ &\quad + [P_1(r^2 + 2\bar{x}^2) + 2P_2\bar{x}\bar{y}][1 + P_3 r^2 + \ldots] \\ \\ y - y_p &= \bar{y} + v_y + \bar{y}(K_1 r^2 + K_2 r^4 + K_3 r^6 + \ldots) \\ &\quad + [2P_1\bar{x}\bar{y} + P_2(r^2 + 2\bar{y}^2)][1 + P_3 r^2 + \ldots] \end{aligned} \tag{7}$$

in which v_x and v_y are photo measuring residuals and,

$$\left.\begin{aligned} \bar{x} &= x^o - x_p \\ \bar{y} &= y^o - y_p \end{aligned}\right\} = \text{observed photo coordinates referred to principal point}$$

$$r = (\bar{x}^2 + \bar{y}^2)^{\frac{1}{2}}.$$

3.0 DEVELOPMENT OF THE IMAGE INTENSIFIER DISTORTION MODEL

3.1 Introduction

Development of a mathematical model to define the systematic error of a system such as the Image Intensifier requires a comprehensive and uniform set of metric data to use as a calibration standard. A stellar photo could provide this standard; however, it is almost impossible to acquire an Image Intensifier photograph of a stellar field that provides a uniformly dense pattern of stellar images which can be measured with equal accuracy.

Therefore, DBA chose to use a set of photographable targets affixed to an ultra-flat 24 inch by 24 inch by 4 inch thick granite surface plate. The relative positions of these targets were determined with an accuracy better than 0.0004 inch using DBA's proprietary Close Range Analytical Calibration system. A 23 by 23 square array of targets spaced at approximately one inch intervals was selected to use as a calibration standard.

3.2 Calibration Data Acquisition and Reduction

During the week of 18-22 October 1971, DBA and Wallops Station personnel obtained both the close range target calibration and the Image Intensifier (system I-09/AC No. 1) photographs of the targeted surface plate. Two sets of acceptable Image Intensifier photographs were eventually obtained by stopping the objective to f/11 and the relay lens to f/4. The first set of three photos were taken at approximately 2:30 P.M. on 22 October with exposure times of 4, 5, and 6 seconds, respectively. Then at approximately 6:00 P.M. on the same date a final set of 11 exposures were taken at 15 minute intervals using a 5 second exposure time. There were some 385 target images, ranging in quality from poor to good, recorded on the Image Intensifier photographs. Typically, the images near the outer edge of the circular format were poor, those in the center were fair, while some images in the intermediate area were good.

Subsequently, these photographs were measured on DBA's 1 micron Mann comparator. Then a series of reductions were made in order to determine the random errors in the data and the systematic errors due to distortions in both the optical and electronic systems of the Image Intensifier. In this system, of course, the distortions of the image tube tremendously outweigh the other two listed sources of error.

The coordinates of all 529 targets on the surface plate were determined to a relative accuracy of better than 0.0004 inch using DBA's Close Range Analytical Calibration programs. Since this level of error propagates into an error of less than 0.75 micrometers on the photograph, which is an order of magnitude smaller than the expected measuring accuracy, the computed coordinates of these targets can be considered as being perfect control points for developing an Image Intensifier distortion model.

Four Image Intensifier photographs were selected to be measured and reduced for use in model development and evaluation. They consisted of the second frame (5-second exposure) from the first set, and frames 2, 6, and 10 of the later set of photos. Hereafter, these four frames are referred to as frames 1, 2, 3 and 4 respectively. Primarily frame 1 was used to develop the model and frames 2, 3, and 4 were used to evaluate model stability over a long (up to 6 hours) period of continuous operating time.

These four frames were reduced using DBA's General Multi-frame Analytical Calibration program, which (in the single frame mode) employes the identical model as that given in Equations (6) and (7), except the direction cosines (λ, μ, and ν) are computed by:

$$\lambda = \frac{X-X^c}{R}$$

$$\mu = \frac{Y-Y^c}{R}$$

$$\nu = \frac{Z-Z^c}{R}$$

in which,

X, Y, Z = coordinates of the i th control target

X^c, Y^c, Z^c = coordinates of the center of projection of the Image Intensifier

and,

$$R = [(X-X^c)^2 + (Y-Y^c)^2 + (Z-Z^c)^2]^{\frac{1}{2}} .$$

This reduction resulted in a set of data (residuals - v_x, v_y) which defined the remaining error in all the measurements. Frame 1 was first reduced exercising the symmetric radial and decentering distortion models, yielding a residual vector rms of 222.4 μm. A vector plot of these residuals is shown in Figure 1. When a similar reduction was made without exercising the parameters K_1, K_2, K_3, P_1 and P_2 of the lens distortion model, a residual vector (Figure 2) of 264.5 μm rms was obtained. Subsequent reductions of frames 2, 3, and 4 (Figures 3, 4, and 5) gave almost identical results with a very similar pattern of residual vectors, indicating that, at this level, the distortion errors were essentially stable over an extended period of time.

3.3 The Image Intensifier Distortion Model

Using the two sets of residual vectors obtained from frame 1, we first applied a third degree general polynomial function of the form:

$$\begin{aligned} \Delta x &= \bar{x} - (a_0 + a_1 x + a_2 y + a_3 xy + a_4 x^2 + a_5 y^2 \\ &\quad + a_6 x^2 y + a_7 xy^2 + a_8 x^3 + a_9 y^3) \\ \Delta y &= \bar{y} - (b_0 + b_1 x + b_2 y + b_3 xy + b_4 x^2 + b_5 y^2 \\ &\quad + b_6 x^2 y + b^7 xy^2 + b_8 x^3 + b_9 y^3) \end{aligned} \tag{8}$$

in which,

$a_0 - a_9$ = coefficients of x polynomial

$b_0 - b_9$ = coefficients of y polynomial

x, y = observed image coordinates

$\bar{x}, \bar{y}$ = true image coordinates $(x + v_x, y + v_y)$

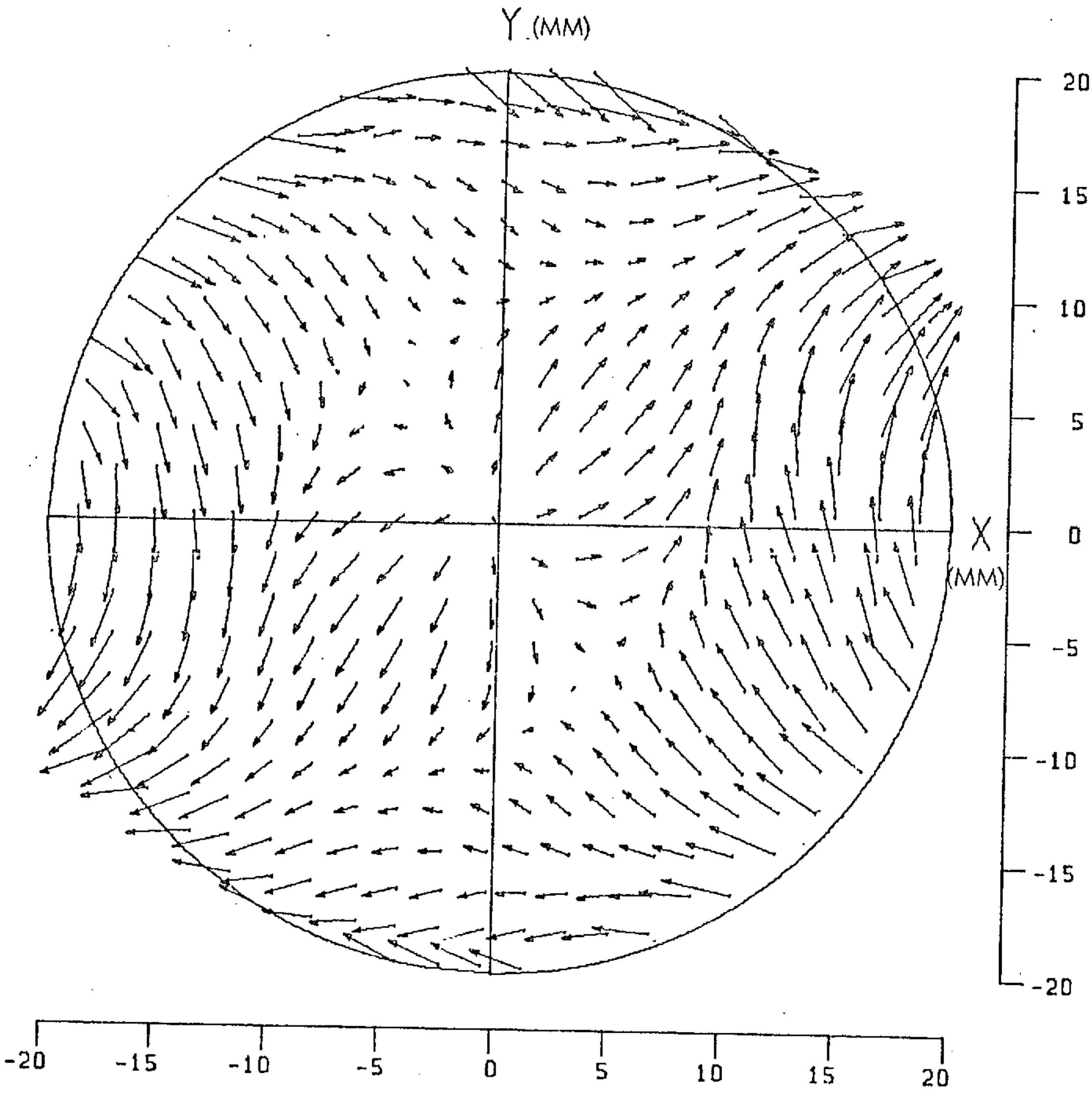
$\Delta x, \Delta y$ = random plus unmodeled systematic components of v_x, v_y.

This procedure met with reasonable success. The rms of residuals $(\Delta x, \Delta y)$ were reduced to about 50μm. However, there were significantly large systematic errors remaining, especially toward the edge of the photo format.

Armed with this encouraging result, the general polynomial model was then extended to fourth degree (15 terms), and then to a fifth degree function (21 terms) with continued success. Surprisingly, the general polynomial function consistently fitted the residual vectors for the case in which the symmetric radial and decentering distortion models were not exercised. With the model extended to a seventh degree general polynomial, the residual vectors Δx, Δy were reduced to an essentially random pattern with an rms value less than 10μm.

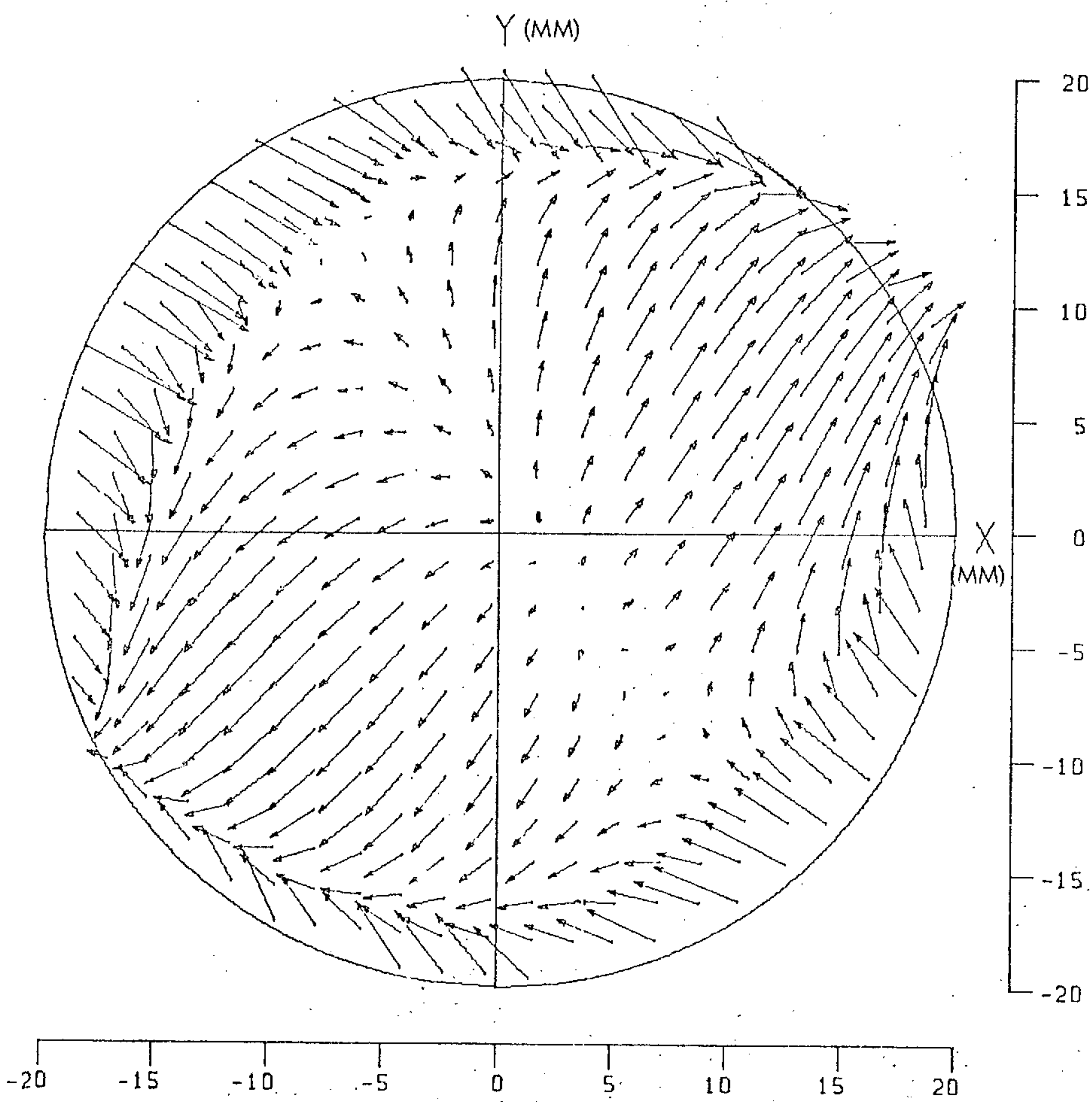
At this point, it is necessary to point out some dangers in applying a function of this degree. First, unless a large number of image points are used (300 to 400 for the initial calibration), the model can become unstable, especially with a few "blunder" type errors (such as an error in control point identification). Also, with 36 terms being determined, the computational effort becomes excessive.

Further analysis showed that when the set of data was restricted to image points within a circle of radius = 17.5 millimeters from photo center, an extension of Equations (8) to fifth degree (using as few as 200 control targets) does an excellent job of removing all known systematic errors from the data. Typically, the rms of $\Delta x, \Delta y$ residual vectors was on the order of 6 to 8 micrometers.



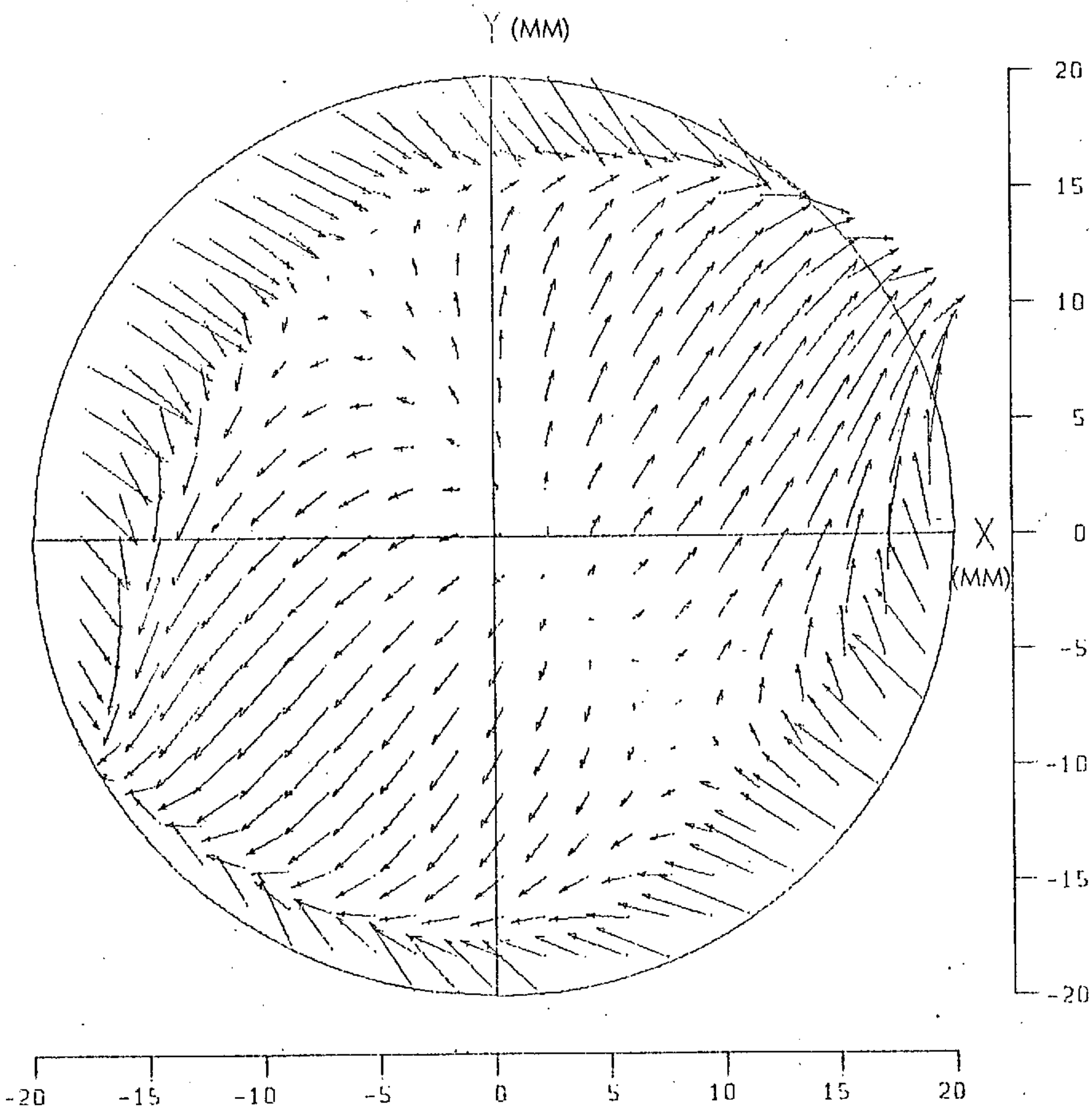
Vector Scale: 1/2 inch = 400 μm RMS = 222.4 μm

FIGURE 1. Plot of residual vectors from frame 1 of targeted surface plate. Symmetric radial (K_1, K_2, K_3) and decentering (P_1, P_2) distortion coefficients are applied.



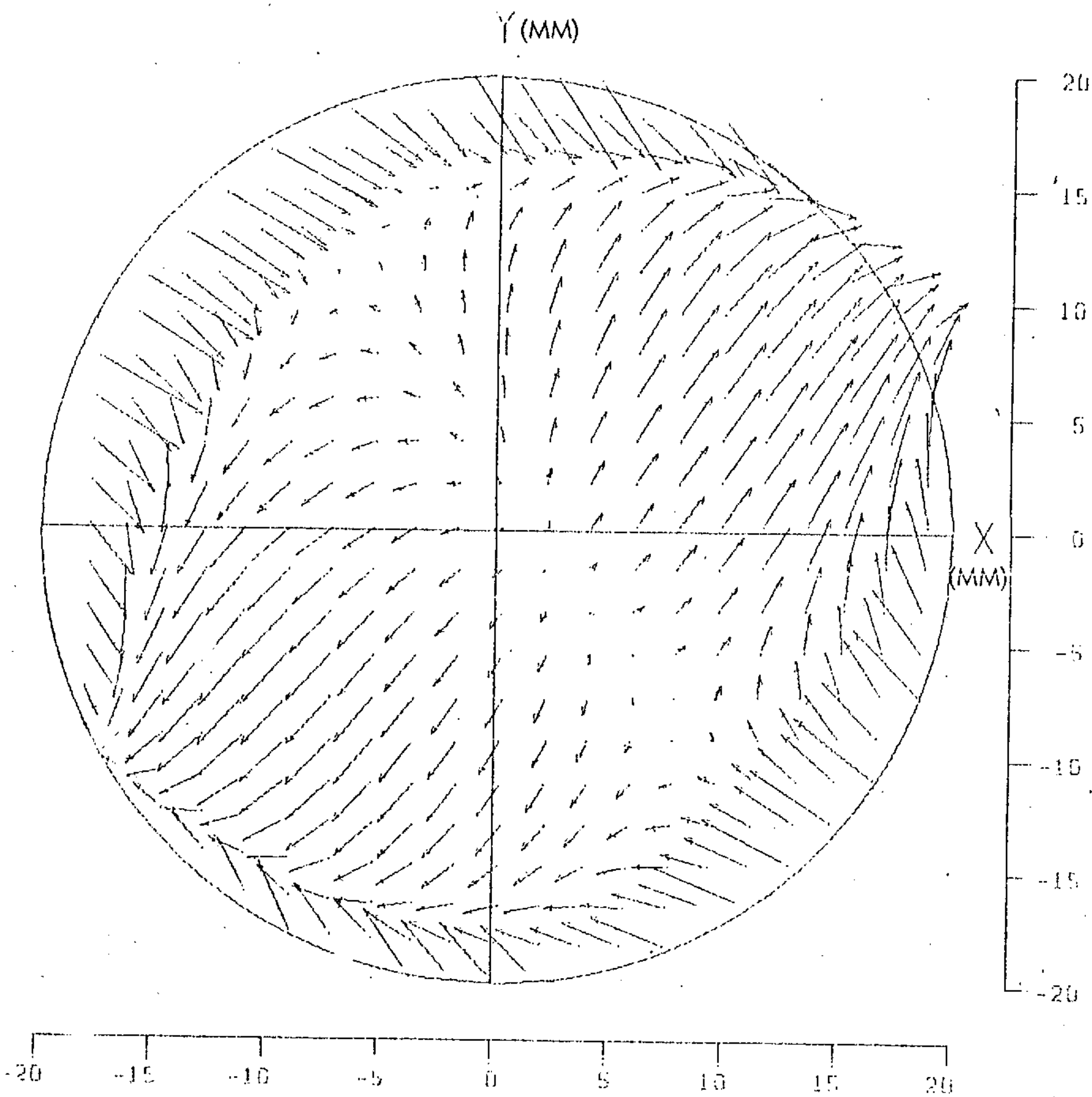
Vector Scale: 1/2 inch = 400 μm RMS = 264.9 μm

FIGURE 2. Plot of residual vectors from frame 1, without model for symmetric radial and decentering distortion.



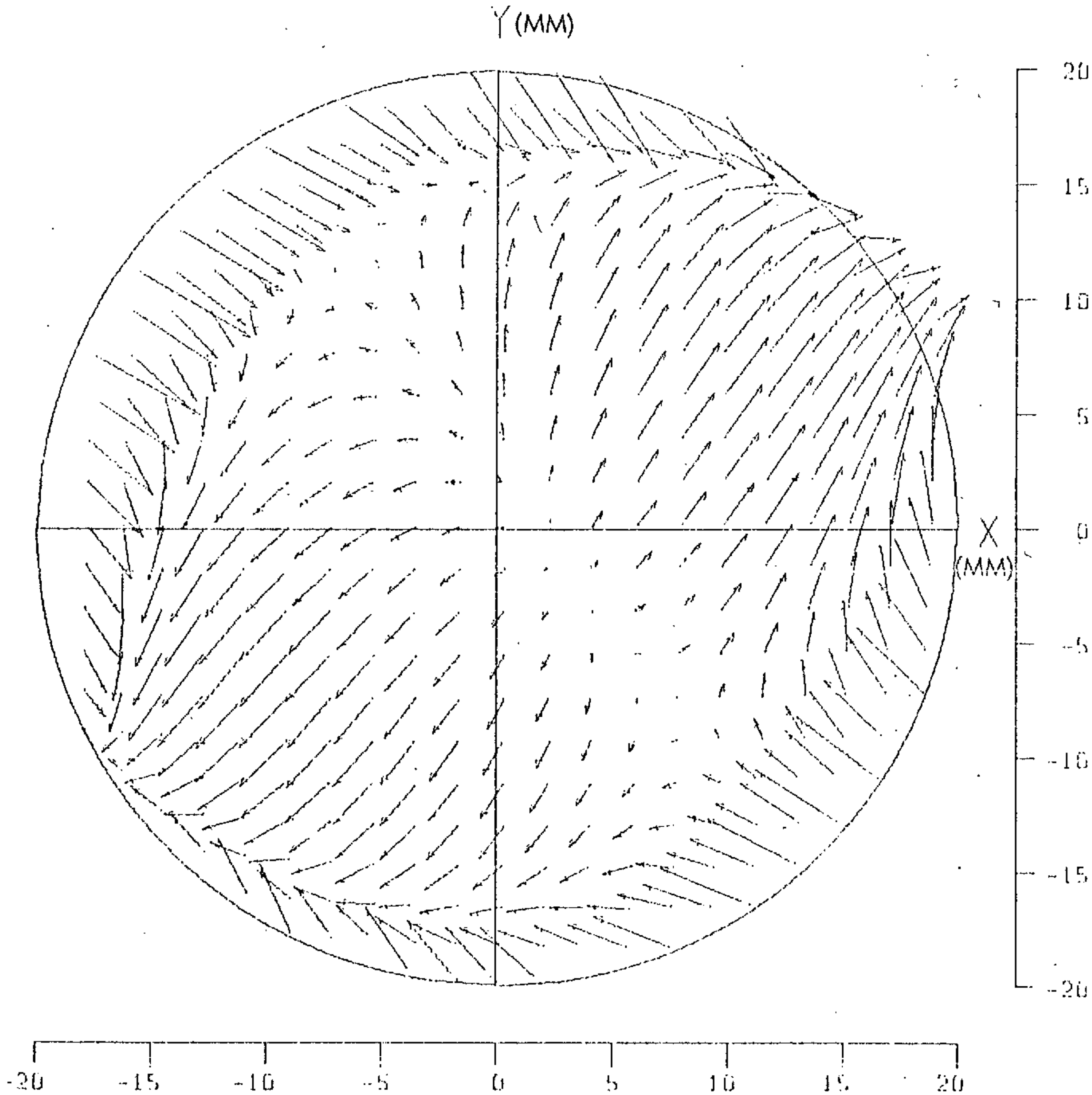
Vector Scale: 1/2 inch = 400 μm   RMS = 261.9 μm

FIGURE 3. Plot of residual vectors from frame 2.



Vector Scale: 1/2 inch = 400 μm RMS = 261.4 μm

FIGURE 4. Plot of residual vectors from frame 3.



Vector Scale: 1/2 inch = 400 μm RMS = 262.0 μm

FIGURE 5. - Plot of residual vectors from frame 4.

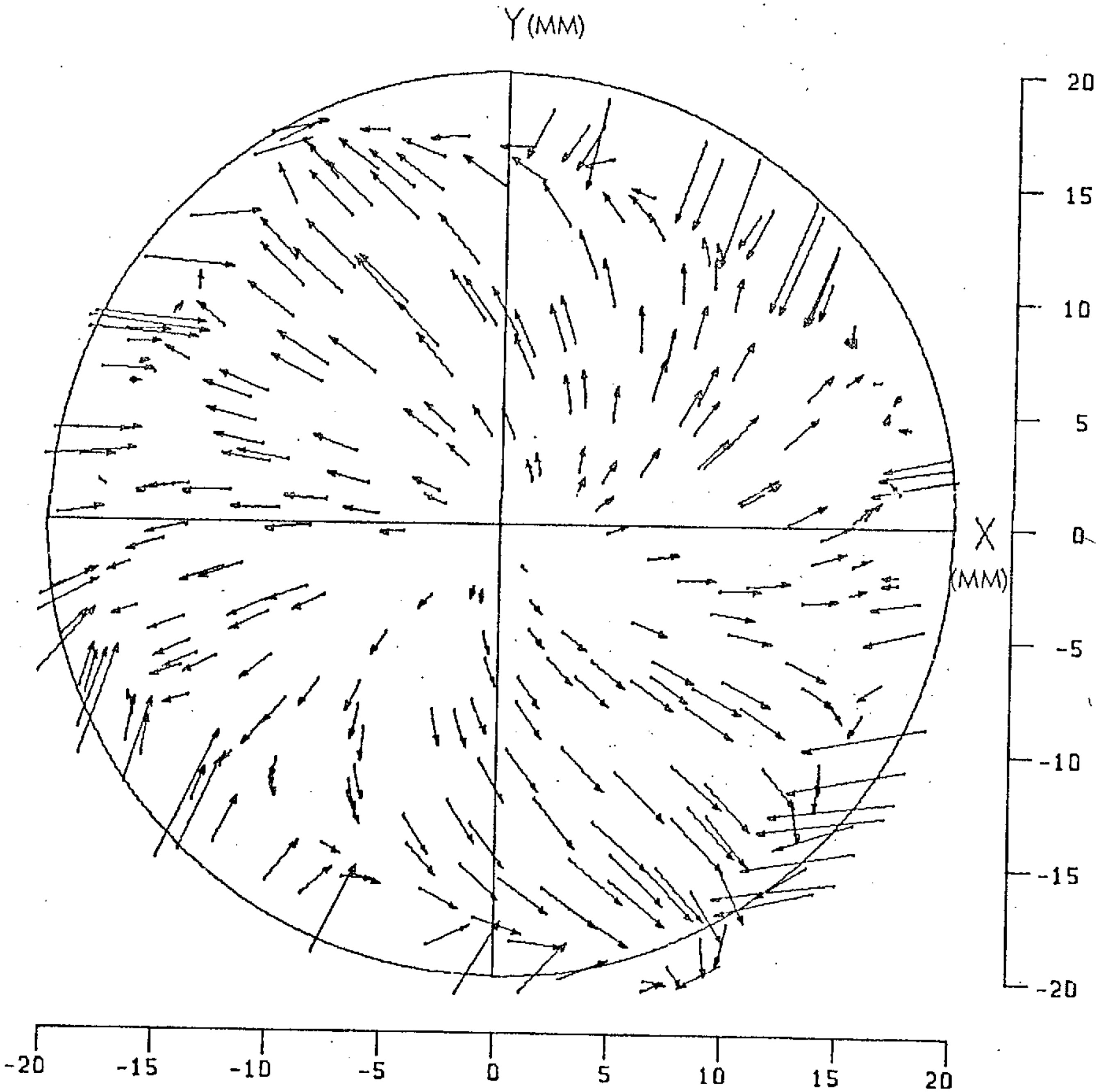
Numerous other mathematical models were investigated but none of them approached the effectiveness of the general polynomial function discussed above. The model suggested by Wong (1969), for use with television systems, in which a pure tangential function was added to the standard optical symmetric radial and decentering functions, showed only slight improvement. Interestingly, Wong, Gamble, and Riggins (1971) report satisfactory use of a fifth degree polynomial with certain insignificant terms eliminated.

3.4 Evaluation of the General Polynomial Model

Data from two stellar photographs were used to evaluate effectivensss of the general polynomial model.

First, a stellar photograph from the same Image Intensifier System (I-09/AC No. 1) with an exposure time of 0.7 second was selected from a series of stellar photos exposed on 18 November 1971. Approximately 400 stellar images were selected in a nearly uniform pattern throughout the photo format. These images were measured and matched with SAO stellar catalog coordinates, in preparation for a reduction similar to that made on the photos from the targeted granite surface plate. The results from this test were very similar to those discussed previously. The rms of residual vectors (Figure 6) was 199.1 μm. When the seventh degree function was applied the rms (Figure 7) dropped to 7.4 μm. Application of the fifth degree function to those points within a circle of 17.5 millimeter radius resulted in an rms (Figure 8) of 7.8 μm.

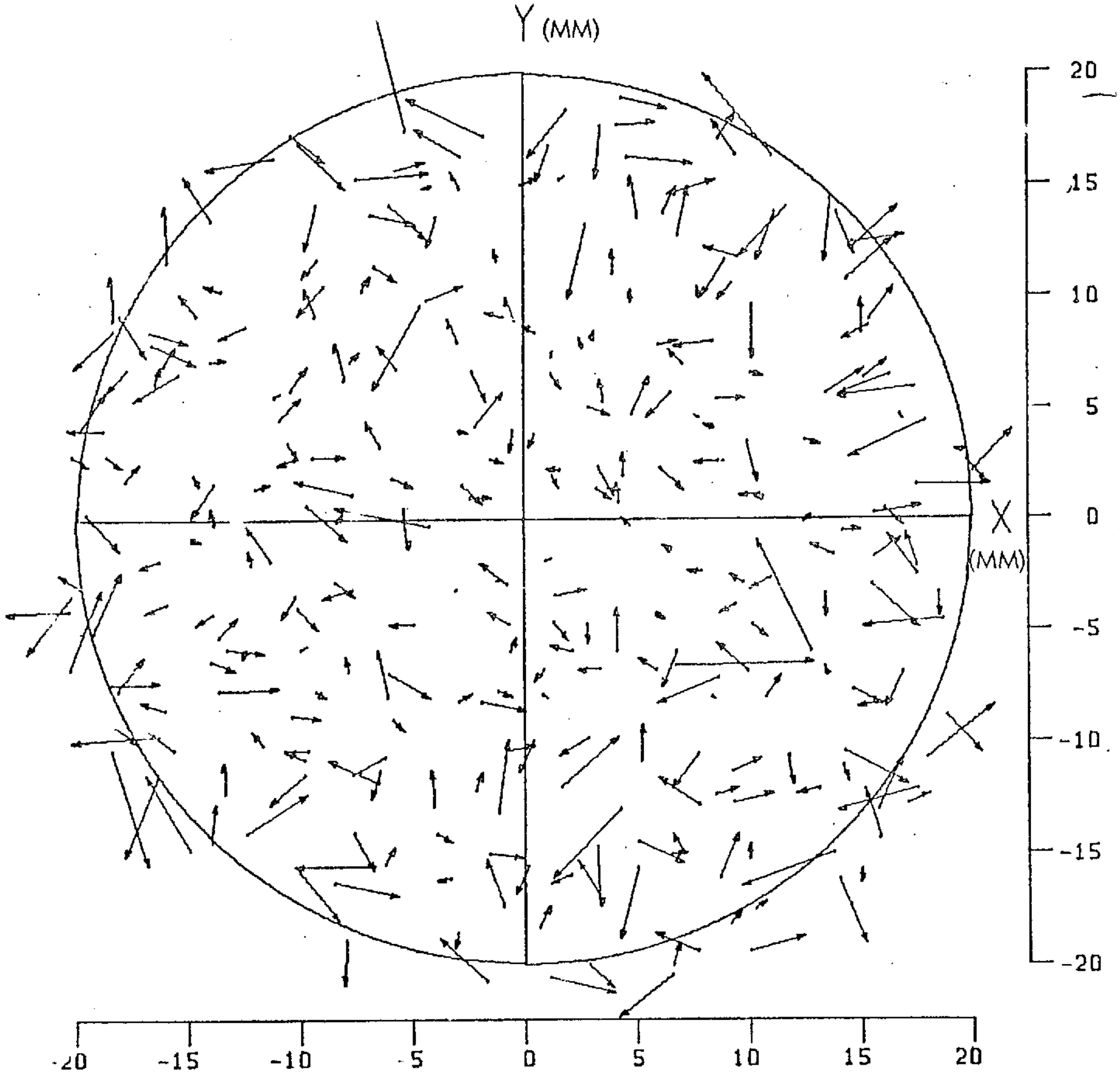
Later, when the distortion model was being implemented on the GE-625 computer at Wallops Station, a set of actual BIC mission data was obtained to test the program modifications. This data was from the Image Intensifier (I-10/H-2) located in Chile during the test. The photograph used contained about 350 images, which were measured and reduced through stellar identification and updating at Wallops. This reduction indicated that system I-10 has considerably less distortion than system I-09. The basic solution (Figure 9) showed an rms of only 146.7 μm. Use of the seventh degree function dropped the rms (Figure 10) to 6.7 μm, and the fifth degree function limited to points within a circle of 17.5 millimeter radius gave an rms (Figure 11) of 7.7 micrometers.



Vector Scale: 1/2 inch = 300 μm

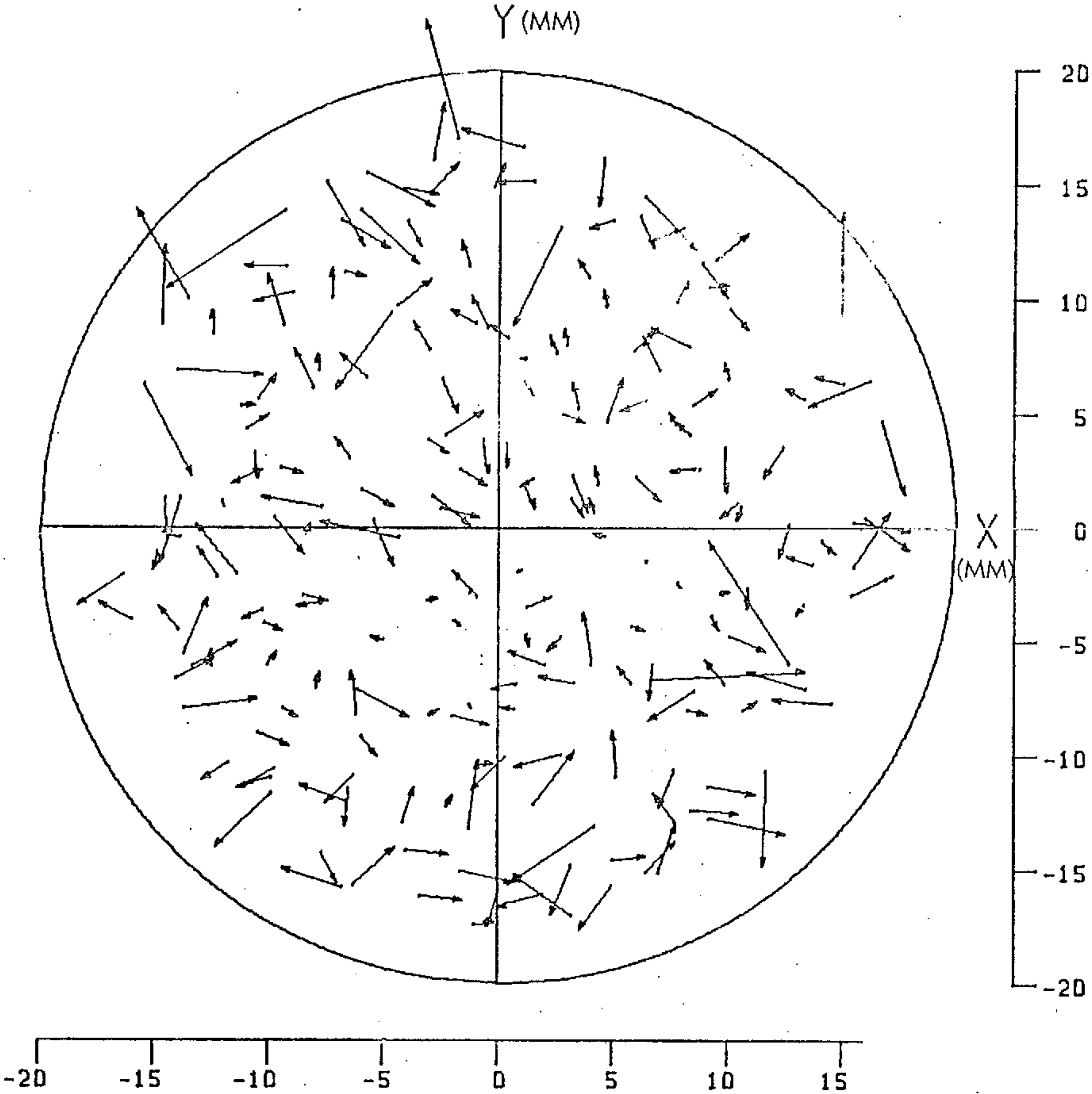
RMS = 199.1 μm

FIGURE 6. Plot of residual vectors from 0.7 second stellar exposure with Image Intensifier System I-09.



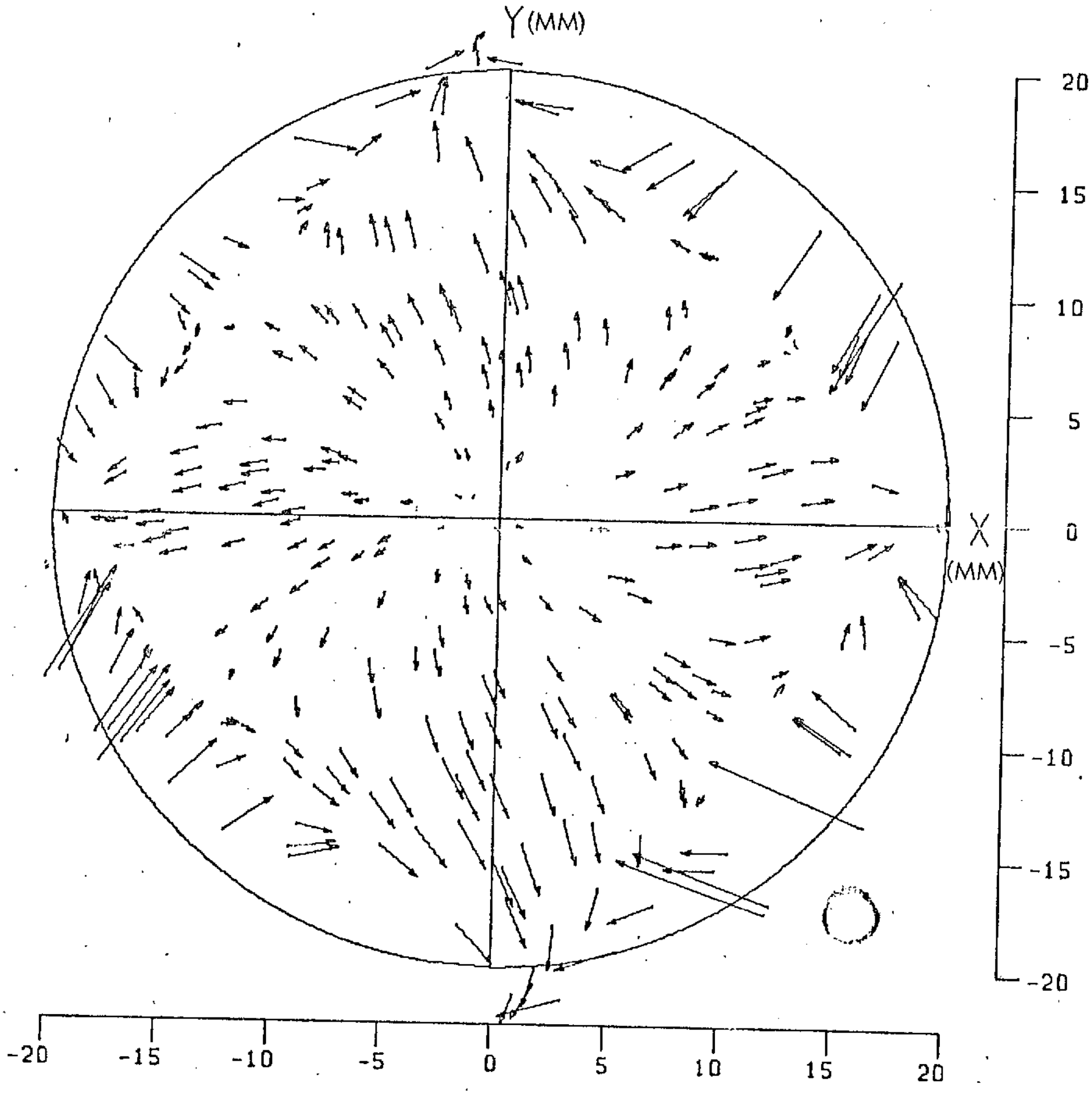
Vector Scale: 1/2 inch = 12.5 μm RMS = 7.4 μm

FIGURE 7. Same as figure 6 after adjustment using 7th order general polynomial.



Vector Scale: 1/2 inch = 12.5 μm RMS = 7.8 μm

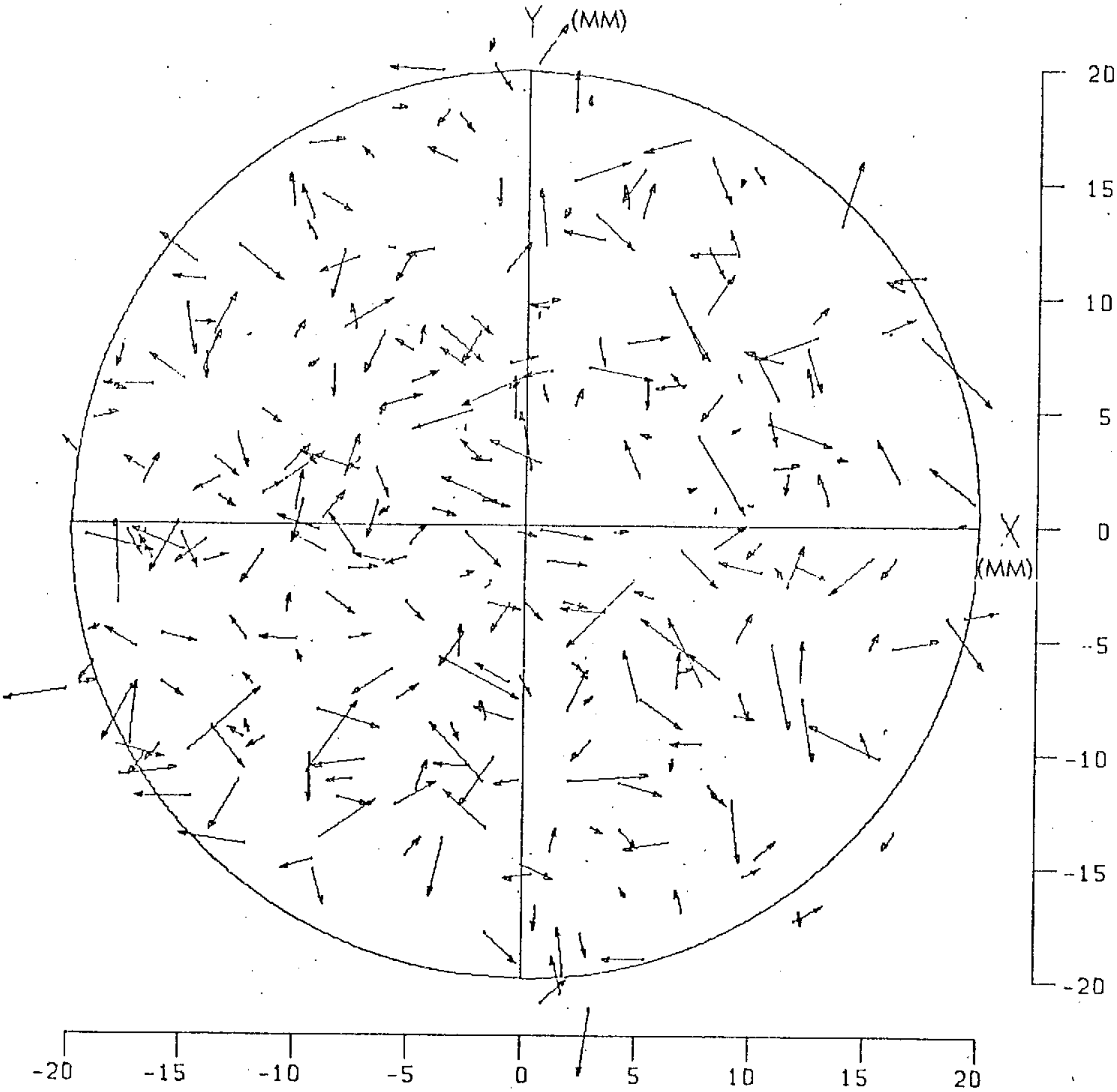
FIGURE 8. Same as figure 6 after adjustment of points within a circle with 17.5 millimeter radius using 5th order general polynomial.



Vector Scale: 1/2 inch = 300 μm

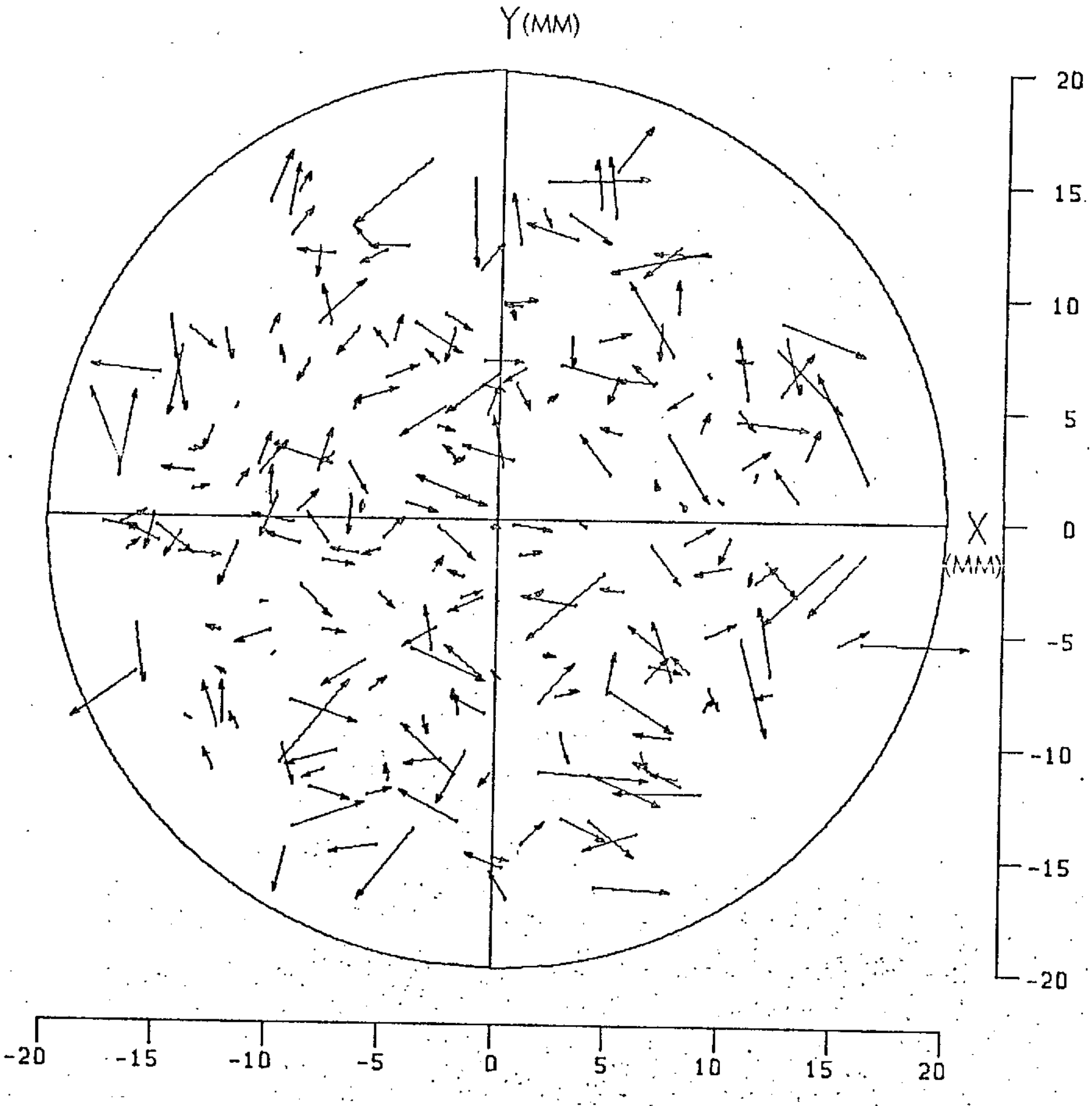
RMS = 146.7 μm

FIGURE 9. Plot of residual vectors from stellar exposure with Image Intensifier System I-10.



Vector Scale: 1/2 inch = 12.5 μm RMS = 6.7 μm

FIGURE 10. Same as figure 9 after adjustment using 7th order general polynomial.



Vector Scale: 1/2 inch = 12.5 μm   RMS = 7.7 μm

FIGURE 11. Same as figure 9 after adjustment of points within a circle with 17.5 millimeter radius using 5th order general polynomial.

4.0 PROGRAM MODIFICATION AND IMPLEMENTATION

4.1 Introduction

Two Wallops programs, (1) The Camera Calibration program and (2) The Camera Orientation program, required some minor modifications to allow effective implementation of the Image Intensifier distortion model. In both programs the changes were made such that the program could be used for either a pure optical system such as the Wallops Triangulation Camera or the Image Intensifier System.

Due to basic differences in the logic of the two programs, specifically the calibration program uses tape or disk file storage as a data interface between program units while the orientation program transfers data through COMMON storage, it was necessary to use slightly different versions of the Image Intensifier calibration sub-program. Also, the calibration program can use data from an unlimited number of frames to determine preliminary distortion coefficients for a single Image Intensifier.

A description of new control and data parameters, modification to existing program units, and implementation of the Image Intensifier distortion program is given in the following sections.

4.2 Calibration Program

4.2.1 Control Program (MAIN)

4.2.1.1 Program Description

Program unit MAIN provides sequencing control for the functional units of the calibration program. Since significant changes were made in MAIN to allow calibration of both optical and Image Intensifier systems, complete listings and flow charts of this program unit are given here.

Up to 20 systems (this was the existing capability) can be calibrated during one computer run. Also, if the Image Intensifier system system is being calibrated, data (up to 500 image points) from an unlimited number of photographs (see use of control parameters NTYPE and NFRM below) can be used.

4.2.1.2 Data

Card 1 - FORMAT (2I5)

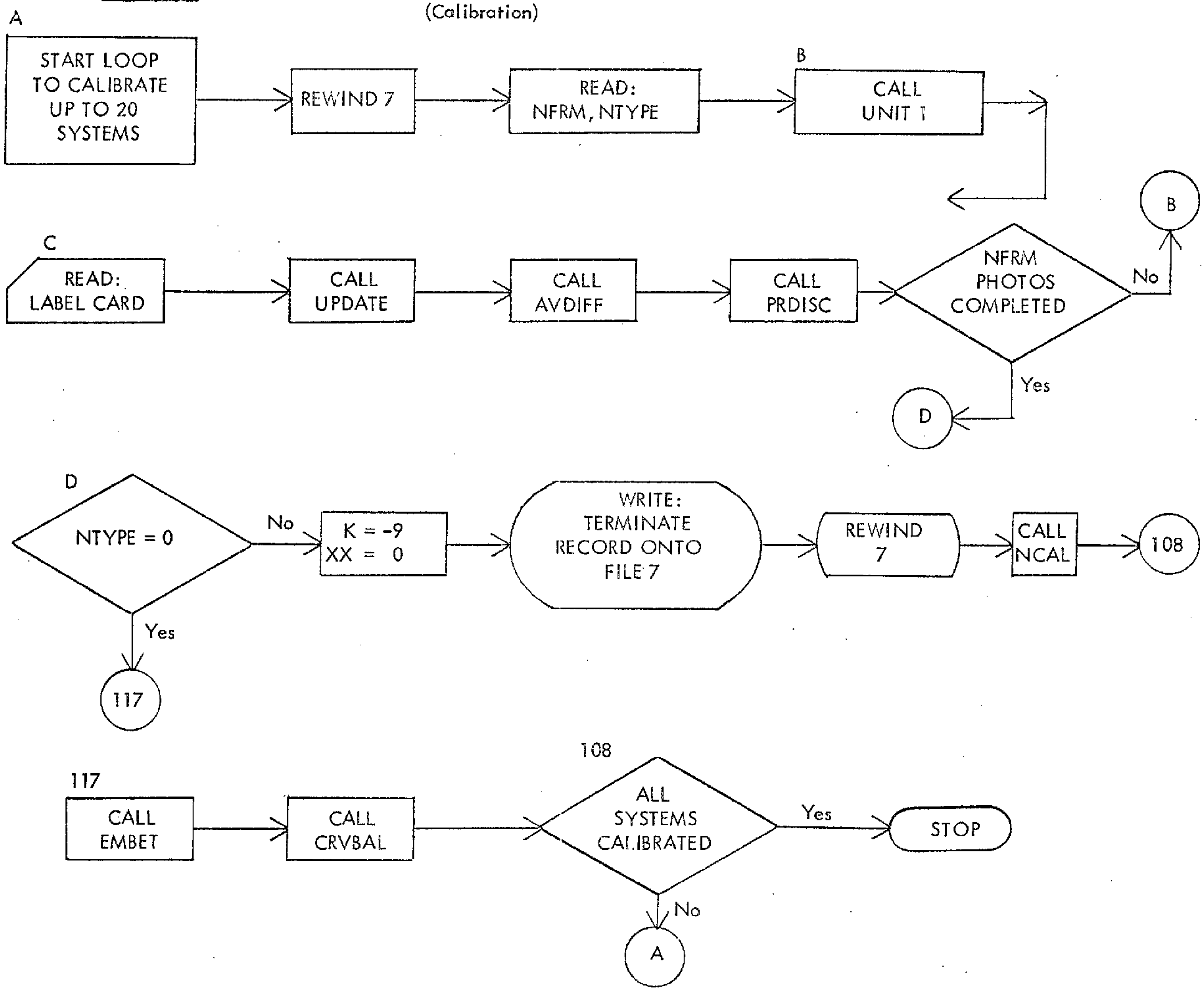
NFRM - Number of frames used for current system. NFRM = 1 for optical systems

NTYPE - Type

0 for optical system
1 for Image Intensifier

4.2.1.3 Flow Chart

Program Unit (MAIN)
(Calibration)



4.2.1.4 Listing

```
C                                   CONTROL PROGRAM (MAIN) FOR CALIBRATION
  101 FORMAT (12H1CALL UPDATE)
  102 FORMAT (12H1CALL AVDIFF)
  103 FORMAT (12H1CALL PRDISC)
  104 FORMAT (12H1CALL EMBET )
  105 FORMAT (12H1CALL CRVBAL)
  106 FORMAT (12H1CALL RETURN)
  107 FORMAT (1X 40H
  110 FORMAT (2I5)
  111 FORMAT (12H1CALL NCAL  )
      DO 108 I=1,20
      REWIND 7
      READ(5,110) NFRM,NTYPE
      DO 115 N=1,NFRM
      CALL UNIT1
      WRITE(6,101)
      READ(5,107)
      WRITE(6,107)
      CALL UPDATE
      WRITE(6,102)
      CALL AVDIFF
      WRITE(6,103)
      CALL PRDISC(AAXX)
  115 CONTINUE
      IF(NTYPE .EQ. 0) GO TO 117
      WRITE(6,111)
      K=-9
      XX = 0.
      WRITE (7) K,XX,XX,XX,XX
      REWIND 7
      CALL NCAL
      GO TO 108
  117 CONTINUE
      IF(AAXX.EQ.1.) GO TO 108
      WRITE(6,104)
      CALL EMBET
      WRITE(6,105)
      WRITE(6,107)
      CALL CRVBAL
      WRITE(6,106)
  108 CONTINUE
      STOP
      END
```

4.2.2 Distortion Calibration Program (PRDISC)

4.2.2.1 Description of Program Changes

Program unit PRDISC has been modified to create a data file for input to the Image Intensifier calibration program NCAL. Also, the program dimensions and loop control parameters have been increased to allow use of as many as 500 control points for each frame. Details of these changes are given in the following sections.

4.2.2.2 Data

Certain new internal parameters have been added to provide an interface with NCAL. These data are described below:

Name	Dimension	Description
IDXY	501	Point identification
XSV	501	Save X and Y coordinates
YSV	501	
VVX	501	Save X and Y residuals
VVY	501	
NVXY	-	Number of points saved
NTSV	-	Number of points saved (temporary)

4.2.2.3 List of Program Changes

Line		Program Statement
7		1 KREJX(501),KREJY(501)
10		DIMENSION IDXY(501),XSV(501),VVX(501),VVY(501)
11		COMMON/BLKS/XSV,YSV,VVX,VVY,IDXY
122		DO 44 I=501
172		NVXY=0
523		NVXY=NVXY+1
524		NTSV=NVXY
525		IF(SVX*SVY)193,191,193
526	191	VVX(NVXY)=0.
527		VVY(NVXY)=0.
528		XSV (NVXY)=0.
529		YSV (NVXY)=0.
530		IDXY(NVXY)=-99
531		GO TO 190
532	193	CONTINUE
533		IDXY(NVXY)=NSTAR
534		XSV (NVXY)=TA*1000.
535		YSV (NVXY)=TB*1000.
536		VVX(NVXY)=VX
537		VVY(NVXY)=VY
653		DO 705 I=1,NTSV
654		IF(IDXY(I))705,705,901
655	701	WRITE(7)IDXY(I),XSV(I),YSV(I),VVS(I),VVY(I)
656	705	CONTINUE
657		I=0
658		XXX=0.
659		WRITE(7)I,XXX,XXX,XXX,XXX

4.2.3 Image Intensifier Distortion Calibration (NCAL)

4.2.3.1 Program Description

Program unit (NCAL) computes the coefficients of an N degree (N<7) general polynomial in X and Y. The general form of the equations used:

$$X(\text{corrected}) = a_0 + a_1 x + a_2 y + \ldots + a_{35} y^7$$

$$Y(\text{corrected}) = b_0 + b_1 x + b_2 y + \ldots + b_{35} y^7$$

are described in further detail in Section 3.0.

The program can use data from an unlimited number of frames, however, no more than 500 points per frame can be used. Data from each frame is used separately to determine a preliminary set of distortion coefficients. Residuals are then computed for all points on this frame and compared with a rejection criterion. If a point is either rejected or restored the solution is recompute with the adjusted data. When all rejections are made for a frame, the normal equation coefficients are accumulated to be used in the simultaneous solution using data from all frames.

4.2.3.2 Data

Program NCAL control data from three cards and the disk file (7) that was formed in program PRDISC.

Card 1 - FORMAT (20A4)

KHEDR - Image Intensifier system identification

Card 2 - FORMAT (I5)

NPNCH - $\begin{cases} 0 & \text{coefficients are \underline{not} punched} \\ 1 & \text{coefficients are punched} \end{cases}$

Card 3 - FORMAT (I5,F10.4)

NX - Number of general polynomial terms to be calibrated ($NX \leq 36$)

RLMT - Points at a distance $(X^2+Y^2)^{\frac{1}{2}} >$ RLMT will <u>not</u> be used in the calibration.

Each record on disk file (7) contains the following data:

a) KPT - point identification;

b) X - x photo measurement;

c) Y - y photo measurement;

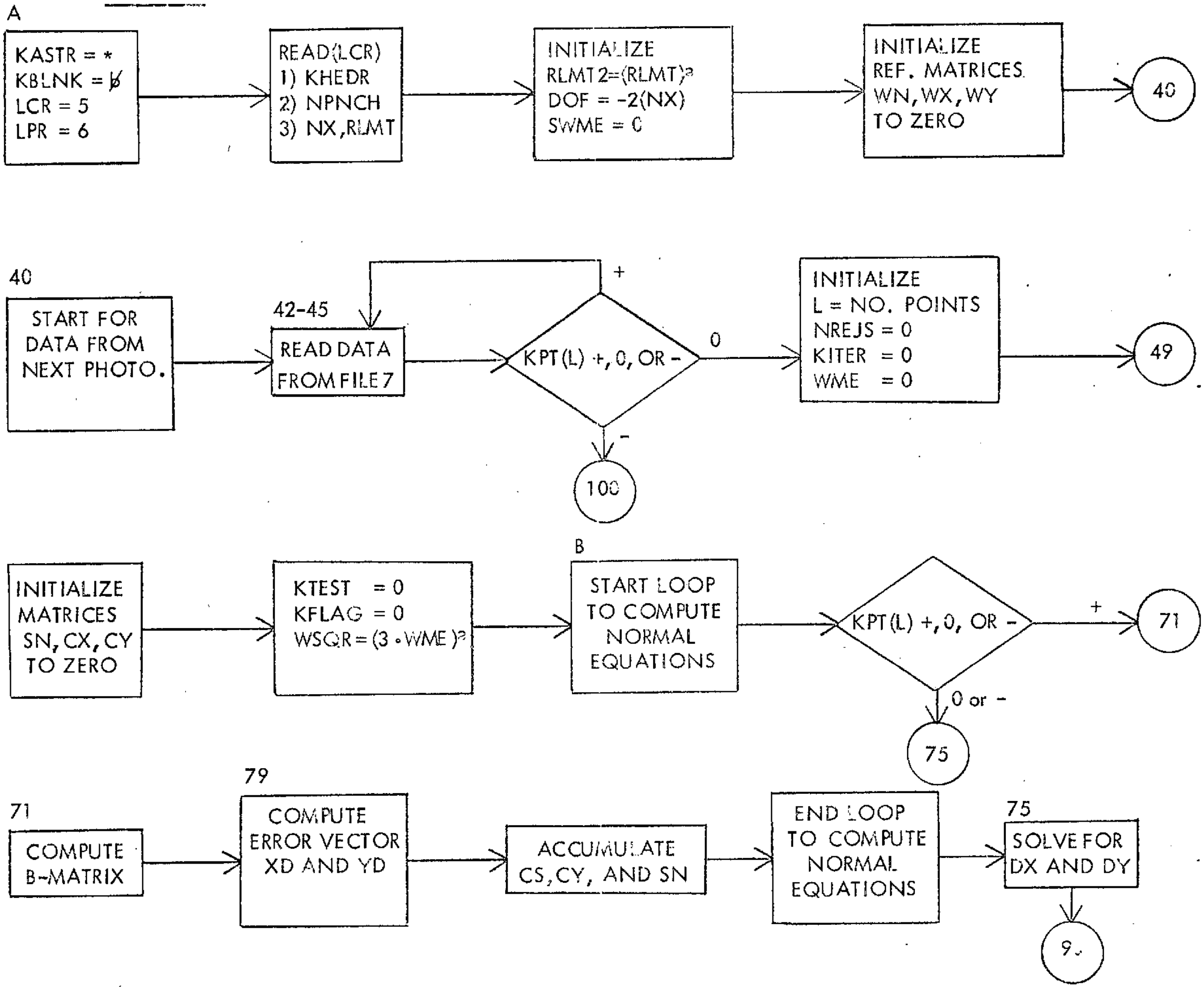
d) VX - error in x measurement;

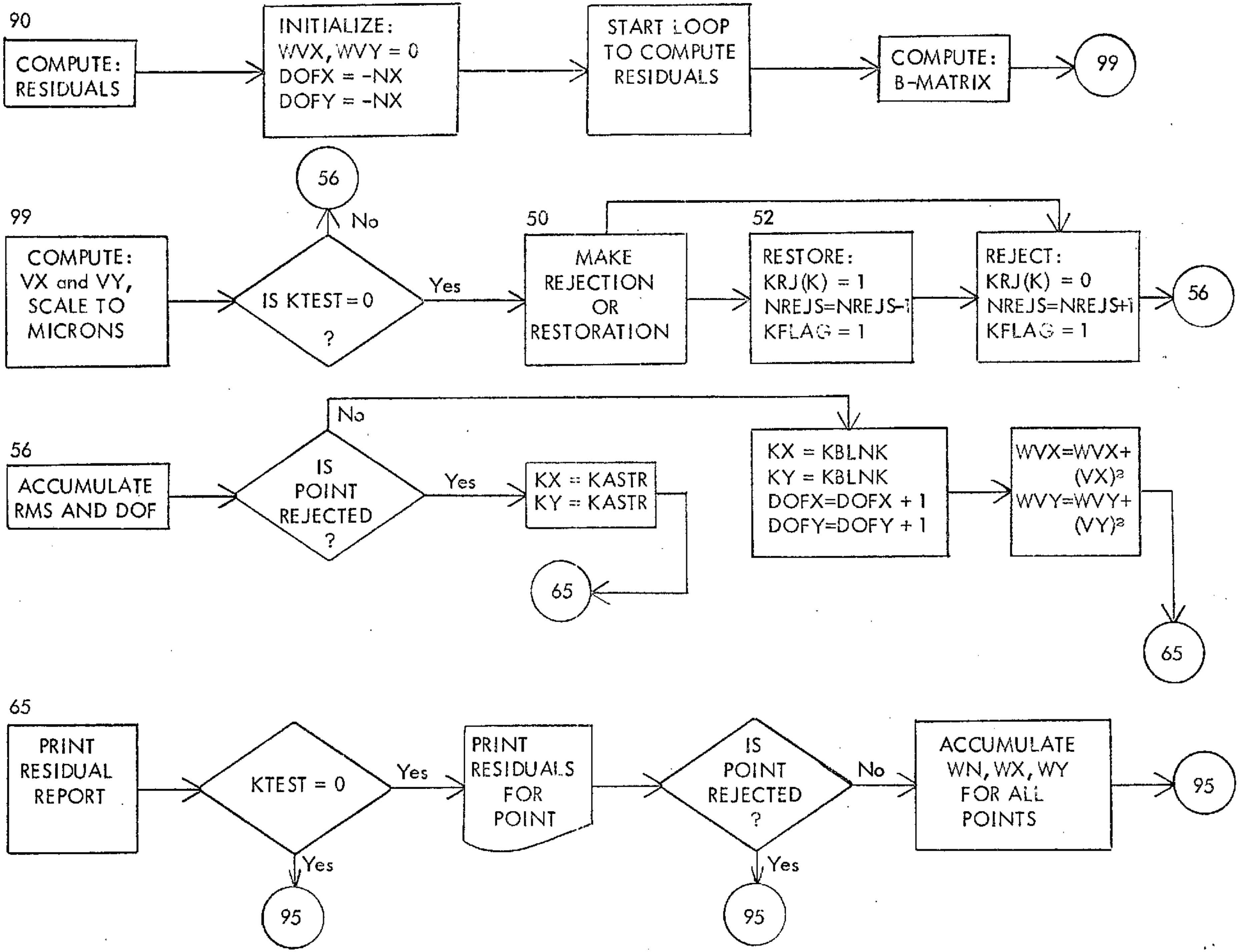
e) VY - error in y measurement.

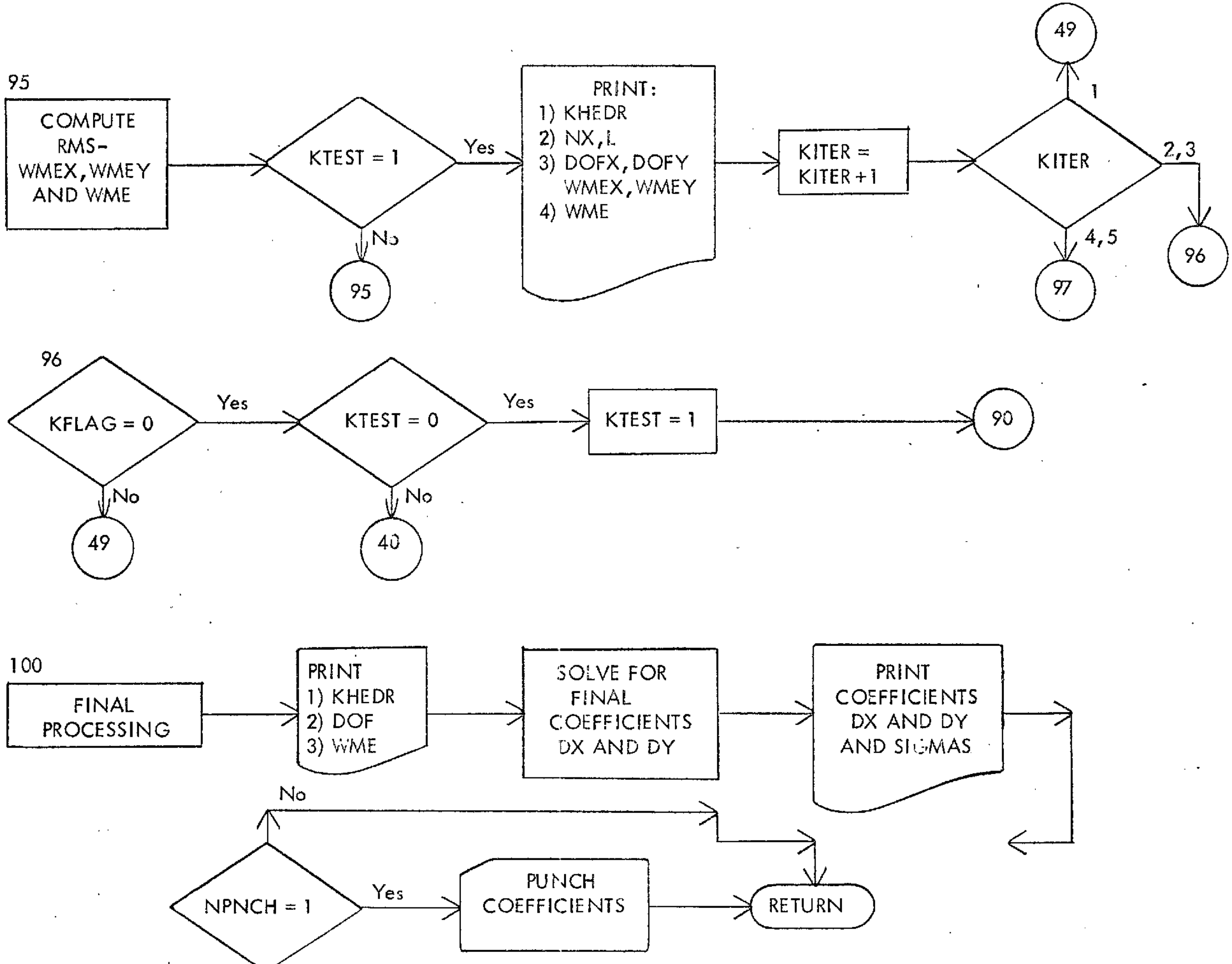
A dummy record with KPT=0 terminates the data for each frame and an additional record with KPT=-9 terminates the entire set for the current calibration.

4.2.3.3 Flow Chart

Subroutine NCAL




90
COMPUTE: RESIDUALS
INITIALIZE: WVX, WVY = 0 DOFX = -NX DOFY = -NX
START LOOP TO COMPUTE RESIDUALS
COMPUTE: B-MATRIX
99
99
COMPUTE: VX and VY, SCALE TO MICRONS
IS KTEST = 0 ?
No
56
Yes
50
MAKE REJECTION OR RESTORATION
52
RESTORE: KRJ(K) = 1 NREJS=NREJS-1 KFLAG = 1
REJECT: KRJ(K) = 0 NREJS=NREJS+1 KFLAG = 1
56
56
ACCUMULATE RMS AND DOF
IS POINT REJECTED ?
No
Yes
KX = KASTR KY = KASTR
65
KX = KBLNK KY = KBLNK DOFX=DOFX + 1 DOFY=DOFY + 1
WVX=WVX+ (VX)²
WVY=WVY+ (VY)²
65
65
PRINT RESIDUAL REPORT
KTEST = 0
Yes
Yes
95
PRINT RESIDUALS FOR POINT
IS POINT REJECTED ?
No
Yes
95
ACCUMULATE WN, WX, WY FOR ALL POINTS
95


95
COMPUTE RMS- WMEX, WMEY AND WME
KTEST = 1
Yes
No
95
PRINT:
1) KHEDR
2) NX, L
3) DOFX, DOFY WMEX, WMEY
4) WME
KITER = KITER + 1
KITER
1
49
2, 3
96
4, 5
97
96
KFLAG = 0
Yes
No
49
KTEST = 0
Yes
No
40
KTEST = 1
90
100
FINAL PROCESSING
PRINT
1) KHEDR
2) DOF
3) WME
SOLVE FOR FINAL COEFFICIENTS DX AND DY
PRINT COEFFICIENTS DX AND DY AND SIGMAS
No
NPNCH = 1
Yes
PUNCH COEFFICIENTS
RETURN

4.2.3.4 <u>Listing</u>

```
C        NCAL
      SUBROUTINE NCAL
C        COMPUTE IMAGE INTENSIFIER CALIBRATION COEFFICIENTS
C        5TH DEGREE GENERAL  POLYNOMIAL
C        USING MATCHING SETS OF  CALIBRATION AND MEAS. COORDINATES
C        CALIBRATED COORDINATES IN (XC,YC)
C        MEASURED COORDINATES IN (X,Y)
C        INTERNAL COMPUTATION IN M. M.
C
      DIMENSION KHEDR(20),WN(1296),KRJ(501)
      DIMENSION XC(501),YC(501),X(501),Y(501),KPT(501)
      DIMENSION SN(1296),DX(36),DY(36),CX(36),CY(36),B(36),WX(36),WY(36)
      COMMON SN,DX,DY,CX,CY,WX,WY,WN
      COMMON/BLKS/ XC,YC,X,Y,KPT,KRJ
C         FORMAT STATEMENTS
    1 FORMAT(1H1)
    2 FORMAT(2E16.8)
    3 FORMAT(5I5)
    4 FORMAT(1X,I5,2X,F9.4,1X,F9.4,2X,F9.4,1X,F9.4,3X,F9.4,1X,F9.4,2X,F6
     *.1,A1,F6.1,A1,3X, F8.1,F8.1,A1,F8.1,A1)
    5 FORMAT(I5,2F10.4,2F8.1)
    6 FORMAT(I5,2F10.4,2F8.1)
    7 FORMAT(/)
    8 FORMAT(1H1,1X,5HPOINT,4X5HX-CAL,5X5HY-CAL,7X5HX-OBS,5X5HY-OBS,
     1  6X6HX-COMP,4X6HY-COMP,6X2HVX,5X2HVY,7X5HRDIST,2X6HRADIAL,
     2   3X5HTANG./)
    9 FORMAT(/18H NO. TERMS USED =   I3/ 20H NO. POINTS USED =  I4//)
   10 FORMAT(2I5,5E16.8,2F12.3)
   11 FORMAT(/22H COMPUTED COEFFICIENTS   /)
   12 FORMAT(20A4)
   14 FORMAT(/14H MEAN ERROR =  F8.1/)
   15 FORMAT(24H X-DEGREES OF FREEDOM = F6.0/  24H Y-DEGREES OF FREEDOM
     1= F6.0/  24H        -X- MEAN ERROR = F8.2/   24H        -Y- MEAN ERR
     2OR = F8.2//)
   16 FORMAT(/22H DEGREES OF FREEDOM = F6.0 /)
C        START
      DATA KASTR,KBLNK/1H*,1H /
      LCR=5
      LPR=6
      IT7=7
      READ (LCR,12) KHEDR
      READ (LCR,3) NPNCH
      READ (LCR,5) NX,RLMT
      NXX=NX*NX
      RLMT2 = RLMT*RLMT
      XX = NX
```

```
      DØF =     +(XX+XX)
      SWME = 0.
      SF3=1000.
C     SET REF. MATRICES TØ ZERØ
      CALL CLEAR (WN,NXX)
      CALL CLEAR (WX,NX)
      CALL CLEAR (WY,NX)
   40 CØNTINUE
C        READ MEASUREMENT DATA
      DØ 45 L=1,501
   42 READ ( IT7 )  KPT(L), X(L), Y(L), VX,VY
      IF(KPT(L))100,46,43
   43 CØNTINUE
      XC(L) = X(L) - VX/ SF3
      YC(L) = Y(L) - VY/ SF3
      KRJ(L) = 1
      IF(X(L)**2 + Y(L)**2 - RLMT2) 45,45,42
   45 CØNTINUE
   46 CØNTINUE
      L = L-1
      NREJS = 0
      KITER = 0
      WME = 50.
   49 CØNTINUE
      CALL CLEAR (CX,NX)
      CALL CLEAR (CY,NX)
      CALL CLEAR(SN,NXX)
      KTEST = 0
      KFLAG = 0
      WSQR = (3.0*WME)**2
C     CØMPUTE NØRMAL EQUATIØNS AND DEGREES ØF FREEDØM
      DØ 75 K=1,L
      IF(KRJ(K)) 75,75,71
   71 CØNTINUE
C     CØMPUTE B(I) MATRIX
      B(1) = 1.
      B(2) = X(K)
      B(3) = Y(K)
      B(4) = X(K)*Y(K)
      B(5) = X(K)*X(K)
      B(6) = Y(K)*Y(K)
      B(7) = B(5)*Y(K)
      B(8) = B(6)*X(K)
      B(9) = B(5)*X(K)
      B(10)= B(6)*Y(K)
      IF (NX .LE. 10) GØ TØ 79
      B(11)= B(9)*Y(K)
      B(12)= B(10)*X(K)
      B(13)= B(7)*Y(K)
```

```
      B(14)= B(9)*X(K)
      B(15)= B(10)*Y(K)
      IF (NX .LE. 15) GØ TØ 79
      B(16)= B(14)*Y(K)
      B(17)= B(15)*X(K)
      B(18)= B(10)*X(K)*X(K)
      B(19)= B(9)*Y(K)*Y(K)
      B(20)= B(14)*X(K)
      B(21)= B(15)*Y(K)
      IF (NX .LE. 21) GØ TØ 79
      B(22)= B(20)*Y(K)
      B(23)= B(21)*X(K)
      B(24)= B(14)*B(6)
      B(25)= B(5)*B(15)
      B(26)= B(9)*B(10)
      B(27)= B(20)*X(K)
      B(28)= B(21)*Y(K)
      IF (NX .LE. 28) GØ TØ 79
      B(29)= B(27)*Y(K)
      B(30)= B(28)*X(K)
      B(31)= B(20)*B(6)
      B(32)= B(21)*B(5)
      B(33)= B(14)*B(10)
      B(34)= B(9)*B(15)
      B(35)= B(27)*X(K)
      B(36)= B(28)*Y(K)
   79 CØNTINUE
      XD    = XC(K)
      YD    = YC(K)
      CALL MATMPY(B,1,NX,B,1,NX,SN,1,1)
      CALL MATMPY(B,1,NX,XD,1,1,CX,1,1)
      CALL MATMPY(B,1,NX,YD,1,1,CY,1,1)
   75 CØNTINUE
C     SET UP XN AND YN  AND INVERT
      CALL MATINV(SN,NX,NX,SN)
      CALL MATMPY(SN,NX,NX,CX,NX,1,DX,0,C)
      CALL MATMPY(SN,NX,NX,CY,NX,1,DY,0,C)
C     CØMPUTE AND PRINT RESIDUALS
C         RETURN FØR FINAL RESIDUAL CØMPUTATIØN
   90 CØNTINUE
      WVX = 0.
      WVY = 0.
      XX=NX
      DØFX = -XX
      DØFY = -XX
      DØ 95 K=1,L
      B(1) =1.
      B(2) =X(K)
      B(3) =Y(K)
```

```
      B(4)  =X(K)*Y(K)
      B(5)  =X(K)*X(K)
      B(6)  =Y(K)*Y(K)
      B(7)  = B(5)*Y(K)
      B(8)  = B(6)*X(K)
      B(9)  = B(5)*X(K)
      B(10)= B(6)*Y(K)
      IF (NX .LE. 10) GO TO 99
      B(11)= B(9)*Y(K)
      B(12)= B(10)*X(K)
      B(13)= B(7)*Y(K)
      B(14)= B(9)*X(K)
      B(15)= B(10)*Y(K)
      IF (NX .LE. 15) GO TO 99
      B(16)= B(14)*Y(K)
      B(17)= B(15)*X(K)
      B(18)= B(10)*X(K)*X(K)
      B(19)= B(9)*Y(K)*Y(K)
      B(20)= B(14)*X(K)
      B(21)= B(15)*Y(K)
      IF (NX .LE. 21) GO TO 99
      B(22)= B(20)*Y(K)
      B(23)= B(21)*X(K)
      B(24)= B(14)*B(6)
      B(25)= B(5)*B(15)
      B(26)= B(9)*B(10)
      B(27)= B(20)*X(K)
      B(28)= B(21)*Y(K)
      IF (NX .LE. 28) GO TO 99
      B(29)= B(27)*Y(K)
      B(30)= B(28)*X(K)
      B(31)= B(20)*B(6)
      B(32)= B(21)*B(5)
      B(33)= B(14)*B(10)
      B(34)= B(9)*B(15)
      B(35)= B(27)*X(K)
      B(36)= B(28)*Y(K)
   99 CONTINUE
      CALL MATMPY(B,1,NX,DX,NX,1,XPI,0,0)
      CALL MATMPY(B,1,NX,DY,NX,1,YPI,0,0)
      VX =(XC(K)-XPI    )*SF3
      VY =(YC(K)-YPI    )*SF3
      IF(KTEST) 50,50,56
   50 CONTINUE
      VSQR=VX**2 + VY**2
C         MAKE REJECTION OR RESTORATION
      IF(KRJ(K)) 51,51,53
   51 IF(VSQR-WSQR) 52,52,56
C         RESTORE
```

```
   52 KRJ(K)=1
      NREJS=NREJS-1
      KFLAG=1
      GO TO 56
   53 CONTINUE
      IF(VSQR-WSQR) 56,56,54
C        REJECT
   54 KRJ(K)=0
      NREJS=NREJS+1
      KFLAG=1
   56 CONTINUE
C        ACCUMULATE RMS AND DEG. OF FREEDOM
      IF(KRJ(K)) 62,62,64
   62 CONTINUE
      KX = KASTR
      KY = KASTR
      GO TO 65
   64 CONTINUE
      KX=KBLNK
      KY=KBLNK
      DOFX = DOFX + 1.
      DOFY = DOFY + 1.
      WVX=WVX+VX*VX
      WVY=WVY+VY*VY
   65 CONTINUE
C       PRINT RESIDUALS IF KTEST = 1
      IF(KTEST) 95,95,91
   91 CONTINUE
      RDIST = SQRT(XPI**2 + YPI**2)
      VRC = (YPI*VY + XPI*VX)/RDIST
      VTC = (XPI*VY - YPI*VX)/RDIST
      WRITE (LPR, 4)KPT(K),XC(K),YC(K),X(K),Y(K),XPI,YPI,VX,KX,VY,KX,
     1    RDIST,VRC,KX,VTC,KX
      IF(KRJ(K)) 95,95,92
   92 CONTINUE
      SWME = SWME + VX**2+VY**2
      DOF = DOF + 2.
      XD     = XC(K)
      YD     = YC(K)
      CALL MATMPY(B,1,NX,B,1,NX,WN,1,1)
      CALL MATMPY(B,1,NX,XD,1,1,WX,1,1)
      CALL MATMPY(B,1,NX,YD,1,1,WY,1,1)
   95 CONTINUE
      WMEX= SQRT(WVX/DOFX)
      WMEY= SQRT(WVY/DOFY)
      WME = SQRT((WVX+WVY)/(DOFX+DOFY))
      IF(KTEST) 89,89,88
   88 CONTINUE
      WRITE (LPR, 7)
```

```
      WRITE(LPR,12) KHEDR
      WRITE(LPR,9) NX,L
      WRITE (LPR, 7)
      WRITE (LPR, 15)DØFX,DØFY,WMEX,WMEY
      WRITE(LPR,14) WME
      WRITE(LPR,7)
   89 CØNTINUE
      KITER=KITER+1
      GØ TØ (93,96,96,97,97),KITER
   93 CØNTINUE
      GØ TØ 49
   96 CØNTINUE
      IF(KFLAG) 97,97,49
   97 CØNTINUE
      IF(KTEST) 98,98,40
   98 CØNTINUE
      KTEST = 1
      WRITE (LPR, 8)
      GØ TØ 90
C        FINAL PRØCESSING FØR ALL FRAMES
  100 CØNTINUE
      WRITE(LPR, 1)
      WRITE(LPR,12) KHEDR
       WME = SQRT(SWME/DØF)
      WRITE(LPR,16) DØF
      WRITE(LPR,14) WME
      CALL MATINV(WN,NX,NX,SN)
      CALL MATMPY(SN,NX,NX,WX,NX,1,DX,0,C)
      CALL MATMPY(SN,NX,NX,WY,NX,1,DY,0,C)
      WRITE(LPR,11)
      NPX=NX+1
      N=0
      DØ 105 M=1,NXX,NPX
      N=N+1
      TA=SQRT(SN(M)) * WME/1000.
      TB=DX(N)/TA
      TC=DY(N)/TA
      WRITE(LPR,10) N,M,DX(N),DY(N),CX(N),CY(N),TA,TB,TC
      IF(NPNCH .EQ. 0) GØ TØ 105
      PUNCH 2,DX(N),DY(N)
  105 CØNTINUE
      RETURN
      END
```

4.3 Orientation Program

4.3.1 Control Program (MAIN)

4.3.1.1 Program Description

Also in this set of programs, program unit MAIN serves a control and sequencing function when determining the orientation of either an optical camera or an Image Intensifier system. The parameter NOJOB continues to control the number of jobs that can be processed with a single computer run. However, additional control and data parameters, described below, are necessary to implement and refine the Image Intensifier distortion model.

4.3.1.2 Data

Card 1 - FORMAT (NAMELIST/N1/)

NOJOB - Number of jobs

Card 2 - FORMAT (I5)

NCAM - Number of systems for which a different set of distortion coefficients will be required

Card 3 - FORMAT (2I5)

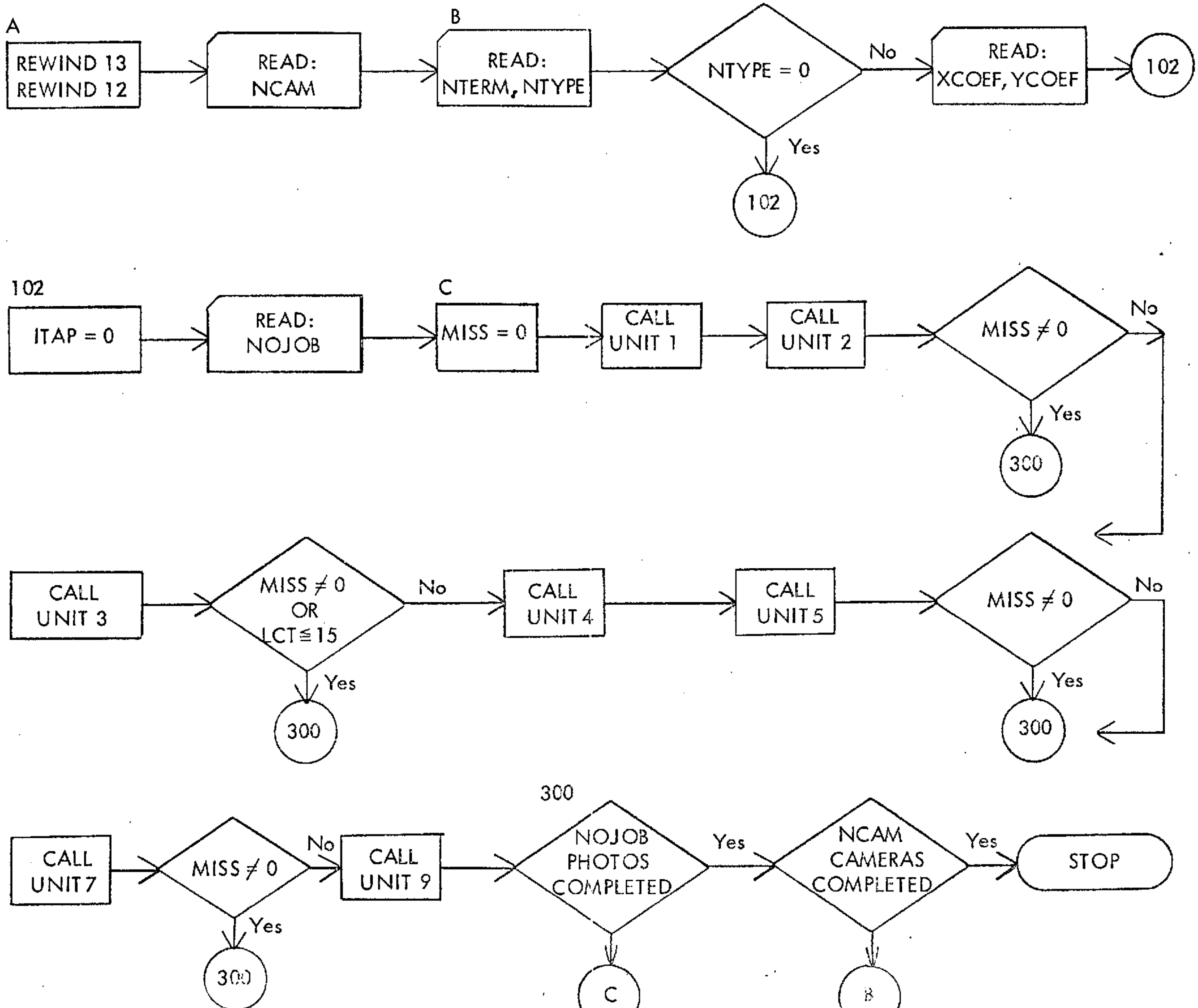
NTERM - Number of terms in the preliminary Image Intensifier distortion calibration

NTYPE - 0 = optical system
1 = Image Intensifier

Card 4 - (3+NTERM) FORMAT (2E16.8)

XCOEF(I)
YCOEF(I) NTERM cards containing preliminary calibration coefficients

4.3 F Chl Pr : UL MA
(Orientation)



4.3.1.4 Listing

```
C                                 CONTROL PROGRAM (MAIN) FOR ORIENTATION
      COMMON/BLK1/CAM,PL,INST,AZ(2),EL(2),ROLL(2),ETAC(4,1),STA
      COMMON/BLK2/ISAT,RMS,ISTR,OBS(3),REF(4),HO,NT,NST
      COMMON/BLK3/IM1(240),IM2(240),NTC1(240),NTC2(240),IXA(240),YA
     1  (240),YA2(240),WY(240),WX(240),XA2(240),SLNT(240)
      COMMON/BLK4/GPHI,GLAM,GAST,STR,KESTH,ESTH,TR,CO,C1,C2,C3
      COMMON/BLK5/GC1(200),WRA(200), WDE(200),RA(200),DE(200)
      COMMON/BLK6/XPO,YPO,XC,YC,CCPO,SIG(10),TK(240),GAM,UWSS
      COMMON/BLK7/AL(2,240),AM(2,240),AN(2,240),XF(4),YF(4)
      COMMON/BK1/P,T,MF(200),XXPRA,CY,XXPDE,TOBL,FRAC,BDY(16)
      COMMON/TRUB/LCT,HC,MISS,RANG(240),SLT
      COMMON/TAP/ITAP,STO,ITY,EQE,LP,NPT(240)
      COMMON/BLKO/NTERM,NTYPE,DXCOEF(36),DYCOEF(36),XCOEF(36),YCOEF(36)
      NAMELIST/N1/NOJOB
C USE  13 IF ITAP=0
      REWIND 13
C USE  12 IF ITAP=1
      REWIND 12
    2 FORMAT(2E16.8)
    3 FORMAT(2I5)
      READ(5,3) NCAM
      DO 500 NC=1,NCAM
      READ(5,3) NTERM,NTYPE
      IF(NTYPE .EQ. 0) GO TO 102
      DO 101 ITN=1,NTERM
  101 READ(5,2) XCOEF(ITN),YCOEF(ITN)
  102 CONTINUE
      ITAP=0
      READ(5,N1)
      DO 300 JOBCT=1,NOJOB
    1 MISS=0
      CALL UNIT1
      CALL UNIT2
```

```
      IF(MISS.NE.0) GO TO 300
      CALL UNIT3
      IF(MISS.NE.0.OR.LCT.GE.15) GO TO 300
      CALL UNIT4
      CALL UNIT5
      IF(MISS.NE.0) GO TO 300
      CALL UNIT7
      IF(MISS.NE.0) GO TO 300
      CALL UNIT9
  300 CONTINUE
  500 CONTINUE
      REWIND 13
      REWIND 12
      STOP
      END
```

4.3.2 Subroutine UNIT2

4.3.2.1 Description of Changes

Subroutine UNIT2, Averaging and Differencing of photo measurements, has been modified to apply the Image Intensifier distortion corrections to all stellar and object data measurements. These corrections do not apply to the automatic stellar search since an alternate set of measured are used by that unit.

4.3.2.2 Data

The following data parameters are available in UNIT2 through COMMON/BLKO/ storage.

NTERM NTYPE	see 4.3.1.2
DXCOEF(36) DYCOEF(36)	not used here
XCOEF(36) YCOEF(36)	see 4.3.1.2

4.3.2.3 List of Program Changes

Line	Program Statement
18	COMMON/BLKO/NTERM, NTYPE, DXCOEF(36), DYCOEF(36), XCOEF(36), YCOEF(36)
140	701 IF(NTYPE.EQ.0) GO TO 704
141 C	APPLY IMAGE INTENSIFIER DIST. COR.
142	AXA=(AXA-XC)*SS2
143	AYA=(AYA-YC)*SS2
144	CALL GPCAL(NTERM,XCOEF,YCOEF,AXA,AYA)
145	AL(1,II)=AXA*SS1+XC
146	AM(1,II)=AYA*SS1+YC
147	GO TO 706
148	704 AL(1,II)=AXA
149	AM(1,II)=AYA
150	706 CONTINUE
156	IF(NTYPE.EQ.0) GO TO 6490
157 C	APPLY IMAGE INTENSIFIER CORRECTION
8	CALL GPCAL(NTERM,XCOEF,YCOEF,AXA,AYA)
9	AXA=AXA*SS1
160	AYA=AYA*SS1
161	GO TO 650
162	6490 CONTINUE

4.3.3 Subroutine UNIT5

4.3.3.1 Description of Changes

Subroutine UNIT5, Preliminary Orientation calibration, has been modified to provide the following functions:

a) apply alternate set of a priori sigmas for principal point (100μm) for Image Intensifier data;

b) allow the solution to converge (i.e. iterate as many as 8 times if necessary) before automatic rejection of point measurements are made;

c) save x,y photo measurements (XSV, YSV) and error in the measurements (VXSV, VYSV) for use in final calibration;

d) apply final calibration (DXCOEF, DYCOEF) coefficients to stellar and object data measurements.

4.3.3.2 Data

The following data parameters are available in Unit 5 through COMMON/BLKO/ and COMMON/BLKS/ storage.

/BLKO/

NTERM NTYPE	see 4.3.1.2
DXCOEF(36) DYCOEF(36)	final calibration coefficients (for this frame only)
XCOEF(36) YCOEF(36)	see 4.3.1.2

/BLKS/

IDXY (501) - save point identification
XSV (501) - save x measurement
YSV (501) - save y measurement
VSXV (501) - save x residual
VYSV (501) - save y residual
KRJXY (501) - set-up point rejection flag

4.3.3.3 List of Program Changes

Line		Program Statement
13		COMMON/BLKO/...
14		COMMON/BLKS/...
15	1	KRJXY(501)
30		KFLAG=0
31		SS3=1000.
32		SS4=1001
33		W(4,1)=1.0D-06
34		W(5,1)=1.0D-06
35		W(6,1)=1.0D-06
36		XCON=2.5
37		IF(NTYPE .EQ. 0) GO TO 503
38		XCON=5.
39		W(4,1)=1.0D-02
40		W(5,1)=1.0D-02
41		W(6,1)=1.0D-08
42	503	CONTINUE
56		ITER=0
57	C	START TO ITERATE SOLUTION...
58	505	ITER=ITER+1
235		DO 173 M=1,6
236		IF(ABS(DD(M,1))-1.0D-07*SQRT(SUMN(M,M))...
237	173	CONTINUE
238		GO TO 178
239	176	CONTINUE
240		IF(ITER-8) 505,178,178
	178	CONTINUE
262		IF(ABS(UWME-CUWME)-0.5) 5,5,6
264		CK=ABS(UWME*XCON)
280		IF(NTYPE .EQ. 0) GO TO 315
281		IF(KFLAG .NE. 0) GO TO 315
282		XPP=XPO*SS2
283		YPP=YPO*SS2
284		LL=ISTR
285		K=LL+1
286		DO 301 I=1,K
287		KRJXY(I)=1
288		IDXY(I)=0
289		XSV(I)=0.

Line Program Statement

```
            YSV(I)=0.
            VXSV(I)=0.
            VYSV(I)=0.
  301       CONTINUE
            DO 305 I=1,LL
            IF(IM1(I)) 306,305,302
  302       IF(WX(I) WY(I)) 304,303,304
  303       KRJXY(I)=0
  304       IDXY(I)=IM1(I)
            XSV(I)=(XA(I)-XPP)*SS4
            YSV(I)=(YA(I)-YPP)*SS4
            VXSV(I)=VVX(I)
            VYSV(I)=VVY(I)
  305       CONTINUE
            I=LL+1
  306       CONTINUE
            IDXY(I)=-99
  308       FORMAT(2X,2I5,2F12.3,2F9.1,2F9.4)
            DO 307 K=1,1
  307       WRITE(6,308) IDXY(K),KRJXY(K),XSV(K),YSV(K),VXSV(K),VYSV(K)
         1    WX(K),WY(K)
            DO 309 K=1,ISAT
  309       WRITE(6,308) K,IM2(K),XA2(K),YA2(K)
            CALL NCALO
C                APPLY ADJUSTED IMAGE INTENSIFIER CORRECTIONS TO STAR MEASUREMENT
            DO 312 K=1,LL
            IF(IM1(K) .EQ. 0) GO TO 311
            TA=(XA(K)-XPP)*SS1
            TB=(YA(K)-YPP)*SS1
            CALL GPCAL (NTERM,DXCOEF,DYCOEF,TA,TB)
            XA(K)=TA*SS2
            YA(K)=TB*SS2
            IF(KRJXY(K)) 310,310,311
  310       WX(K)=0.
            WY(K)=0.
  311       CONTINUE
            WRITE(6,308) K,IM1(K),XA(K),YA(K),WX(K),WY(K)
  312       CONTINUE
C                APPLY ADJUSTED IMAGE INTENSIFIER CORRECTIONS TO TARGET
                                                                   MEASUREMENTS
            DO 314 K=1,ISAT
```

Line Program Statement

```
      TA=(XA2(K)-XPP)*SS1
      TB=(YA2(K)-YPP)*SS1
      CALL GPCAL (NTERM,DXCOEF,DYCOEF,TA,TB)
      XA2(K)=TA*SS2
      YA2(K)=TB*SS2
      WRITE(6,308) K,IM2(K),XA2(K),YA2(K)
314   CONTINUE
      XPO=0
      YPO=0
      KFLAG=1
      GO TO 49
315   CONTINUE
```

4.3.4 Subroutine GPCAL

4.3.4.1 Description

Subroutine GPCAL is used by subroutine UNIT2 and subroutine UNIT5 to apply correct both stellar and object data measurements for error due to Image Intensifier distortions.

Using a set of NTERM coefficients, either (XCOEF, YCOEF) or (DXCOEF, DYCOEF), and photo measurements (x, y) a corrected set of photo coordinates are computed by:

$$X(\text{corrected}) = a_0 + a_1 x + a_2 y + a_3 xy + \ldots + a_{35} y^7$$

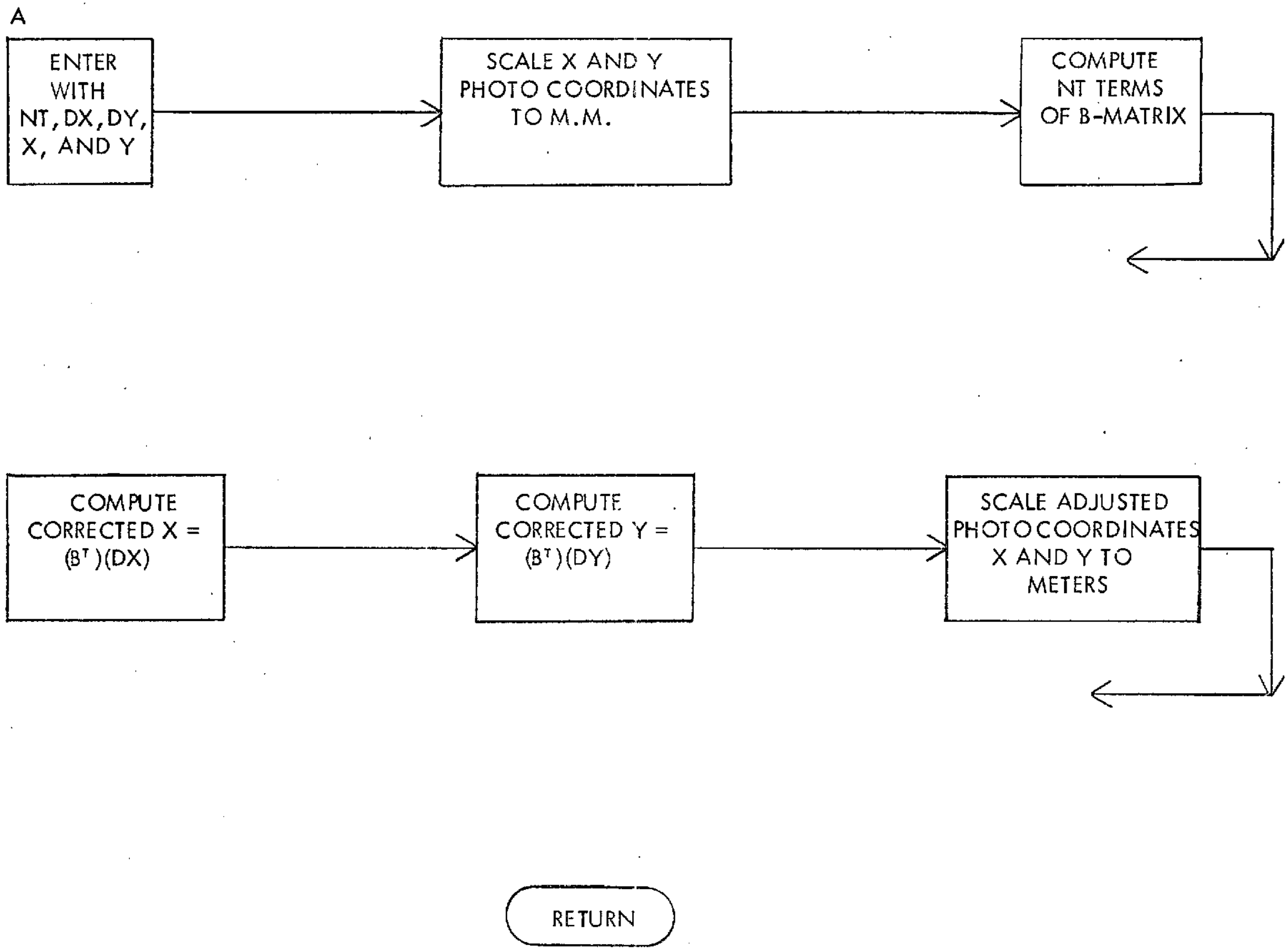
$$Y(\text{corrected}) = b_0 + b_1 x + b_2 y + b_3 xy + \ldots + b_{35} y^7$$

where $a_0 - a_{35}$ represent DYCOEF or YCOEF.

4.3.4.2 Data

NT	-	number of coefficients in calibration
DX(36)	-	up to 36 x coefficients
DY(36)	-	up to 36 y coefficients
XX	-	x photo coordinates (meters)
YY	-	y photo coordinates (meters)

4.3.4.3 Flow Chart Subroutine GPCAL



4.3.4.4 Listing

```
SUBRØUTINE GPCAL(NT,DX,DY,XX,YY)
SUBRØUTINE TØ APPLY GENERAL PØLY. CØRRECTIØNS - UP TØ 5TH DEGREE
   INPUT AND ØUTPUT IN METERS.
   INTERNAL CØMPUTATIØNS IN M.M.
DIMENSIØN B(36),DX( 1),DY( 1)
SF3=1000.
X=XX*SF3
Y=YY*SF3
B(1) =1.
B(2) =X
B(3) =Y
B(4) = X*Y
B(5) = X*X
B(6) = Y*Y
B(7) = B(5)*Y
B(8) = B(6)*X
B(9) = B(5)*X
B(10)= B(6)*Y
IF (NT .LE. 10) GØ TØ 99
B(11)= B(9)*Y
B(12)= B(10)*X
B(13)= B(7)*Y
B(14)= B(9)*X
B(15)= B(10)*Y
IF (NT .LE. 15) GØ TØ 99
B(16)= B(14)*Y
B(17)= B(15)*X
B(18)= B(10)*B(5)
B(19)= B(9)*B(6)
B(20)= B(14)*X
B(21)= B(15)*Y
IF (NT .LE. 21) GØ TØ 99
B(22)= B(20)*Y
B(23)= B(21)*X
B(24)= B(14)*B(6)
B(25)= B(5)*B(15)
B(26)= B(9)*B(10)
B(27)= B(20)*X
B(28)= B(21)*Y
IF (NT .LE. 28) GØ TØ 99
B(29)= B(27)*Y
B(30)= B(28)*X
B(31)= B(20)*B(6)
B(32)= B(21)*B(5)
B(33)= B(14)*B(10)
```

```
      B(34)= B(9)*B(15)
      B(35)= B(27)*X
      B(36)= B(28)*Y
   99 CONTINUE
      CALL MATMPY(B,1,NT,DX,NT,1, X ,0,0)
      CALL MATMPY(B,1,NT,DY,NT,1, Y ,0,0)
      XX=X/SF3
      YY=Y/SF3
      RETURN
      END
```

4.3.5 Subroutine NCALO

4.3.5.1 Description

Subroutine NCALO is identical to program unit NCAL (see Section 4.2.3) except (1) the data required in NCALO is stored in COMMON blocks (BLKO) and (BLKS) and (2) NCALO uses data from only one photograph to compute a final calibration to be used only with that photo. The coefficients obtained here are used by subroutine UNIT5, preliminary orientation calibration, to apply the final corrections to both stellar and object data (target) coordinates.

4.3.5.2 Data

/BLKO/

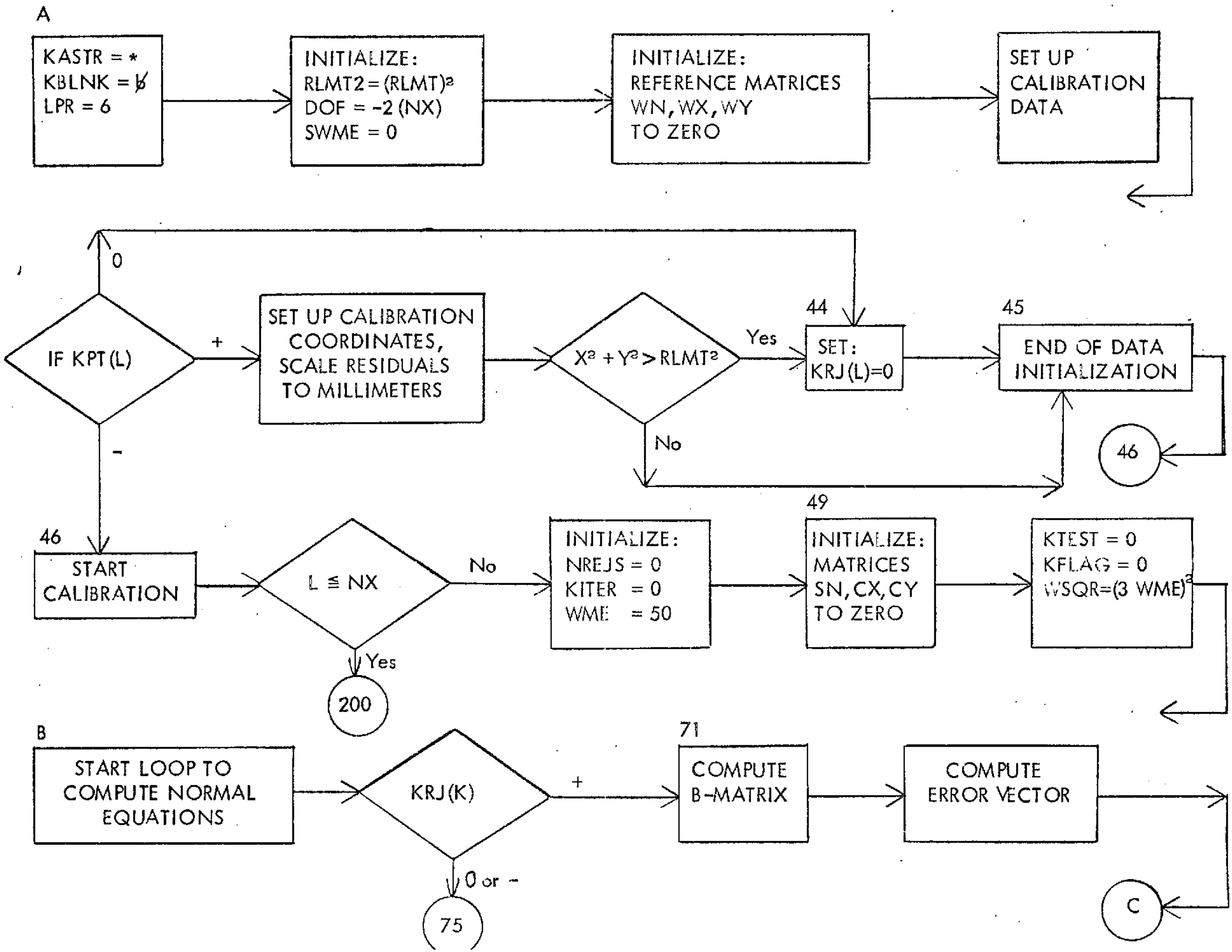
NX	-	number of terms in calibration
NTYPE	-	not used here
DX(36)	-	final x coefficients
DY(36)	-	final y coefficients
DXO(36)	-	not used here
DYO(36)	-	not used here

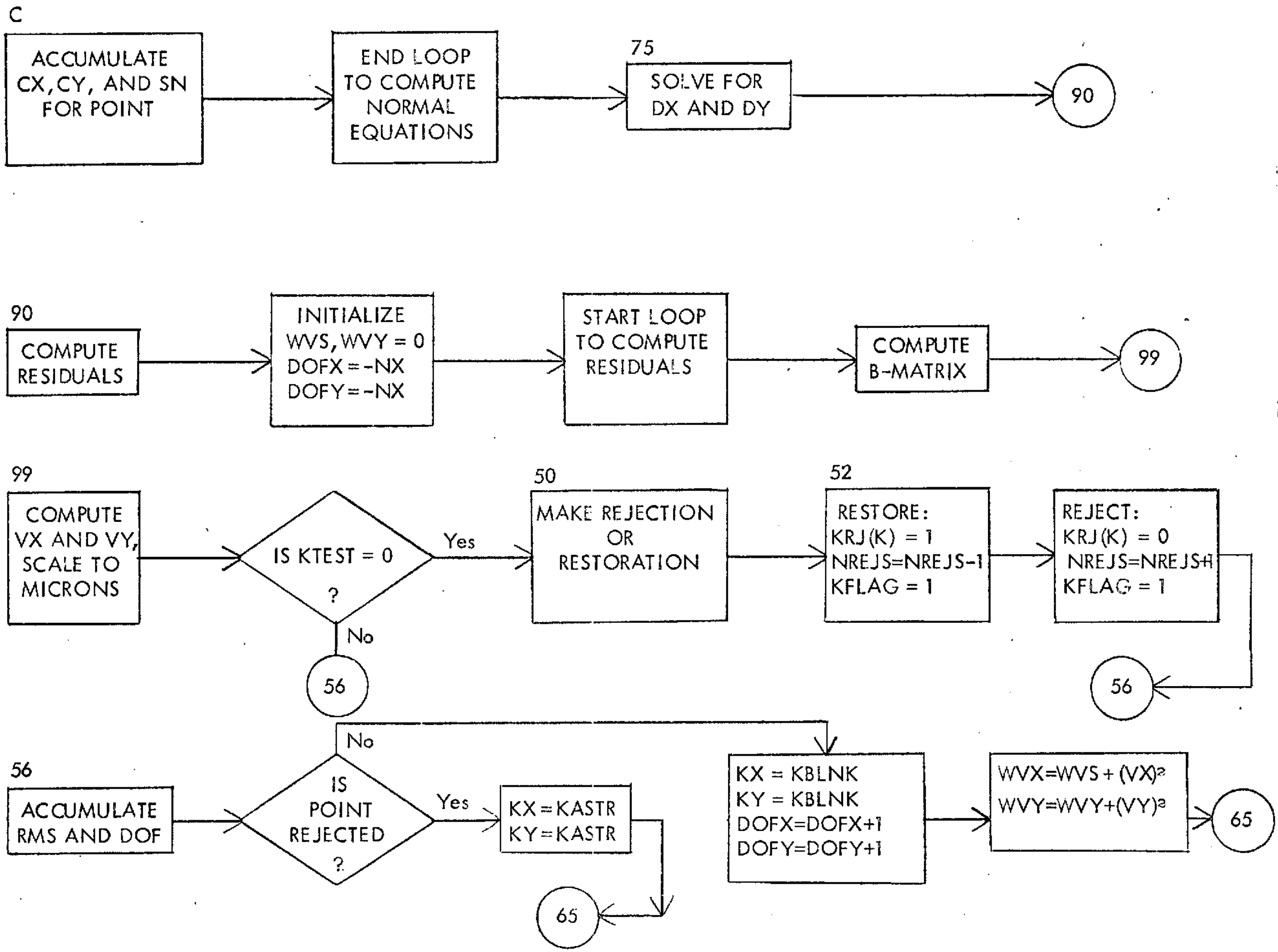
/BLKS/

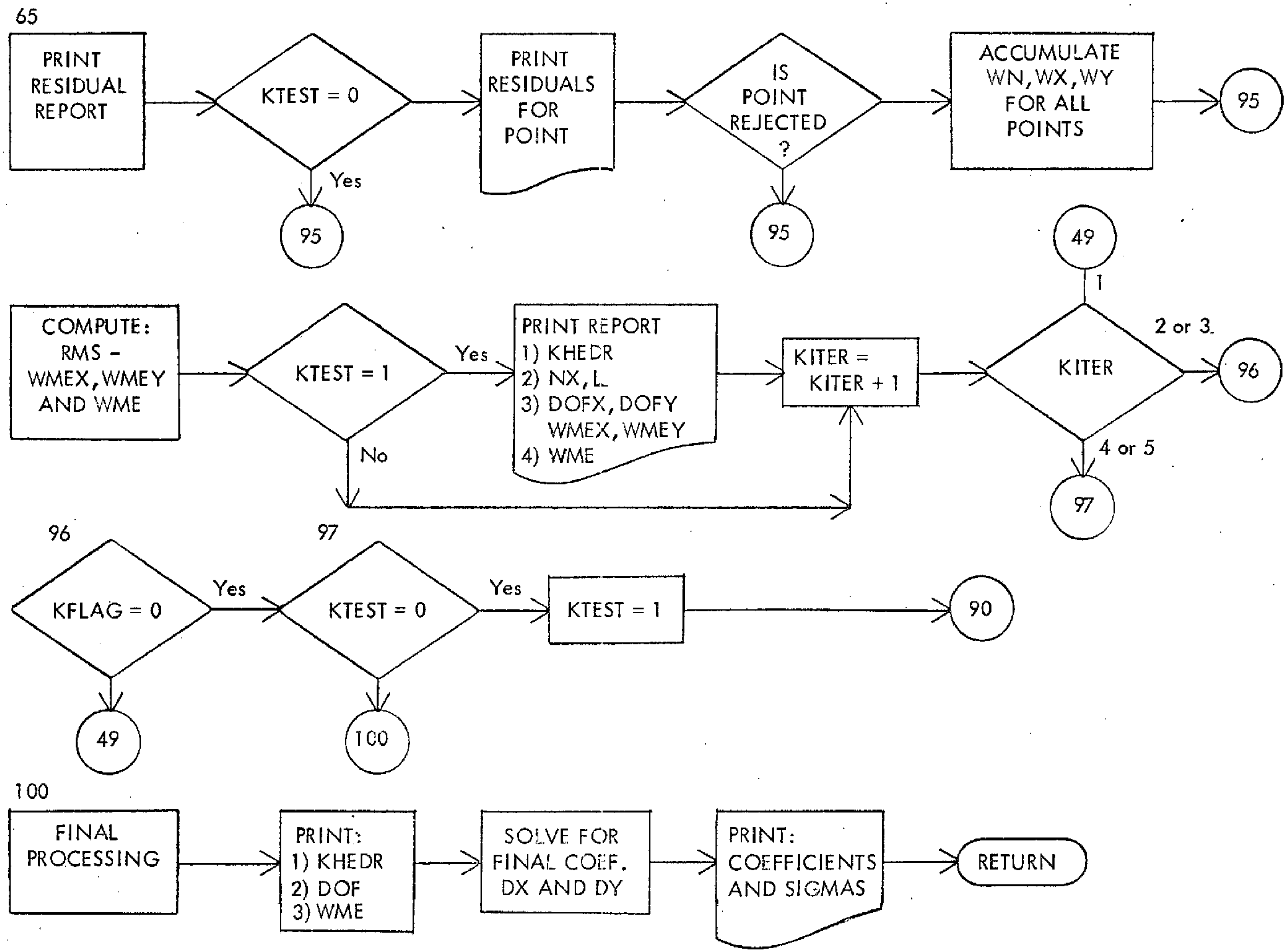
KPT(501)	-	point identification
X(501)	-	x photo measurement
Y(501)	-	y photo
XC(501)	-	x (true)
YC(501)	-	y (true)
KRJ(501)	-	rejection code

4.3.5.3 Flow Chart

Subroutine NCALO




C
ACCUMULATE CX, CY, AND SN FOR POINT
END LOOP TO COMPUTE NORMAL EQUATIONS
75
SOLVE FOR DX AND DY
90
90
COMPUTE RESIDUALS
INITIALIZE WVS, WVY = 0 DOFX = -NX DOFY = -NX
START LOOP TO COMPUTE RESIDUALS
COMPUTE B-MATRIX
99
99
COMPUTE VX AND VY, SCALE TO MICRONS
IS KTEST = 0 ?
Yes
No
56
50
MAKE REJECTION OR RESTORATION
52
RESTORE: KRJ(K) = 1 NREJS=NREJS-1 KFLAG = 1
REJECT: KRJ(K) = 0 NREJS=NREJS+1 KFLAG = 1
56
56
ACCUMULATE RMS AND DOF
IS POINT REJECTED ?
No
Yes
KX = KASTR KY = KASTR
65
KX = KBLNK KY = KBLNK DOFX=DOFX+1 DOFY=DOFY+1
WVX=WVS + (VX)²
WVY=WVY+(VY)²
65


65
PRINT RESIDUAL REPORT
KTEST = 0
Yes
95
PRINT RESIDUALS FOR POINT
IS POINT REJECTED ?
95
ACCUMULATE WN, WX, WY FOR ALL POINTS
95
COMPUTE: RMS - WMEX, WMEY AND WME
KTEST = 1
Yes
No
PRINT REPORT
1) KHEDR
2) NX, L
3) DOFX, DOFY WMEX, WMEY
4) WME
KITER = KITER + 1
49
1
KITER
2 or 3
96
4 or 5
97
96
KFLAG = 0
Yes
49
97
KTEST = 0
Yes
100
KTEST = 1
90
100
FINAL PROCESSING
PRINT:
1) KHEDR
2) DOF
3) WME
SOLVE FOR FINAL COEF. DX AND DY
PRINT: COEFFICIENTS AND SIGMAS
RETURN

4.3.5.4 Listing

```
C          NCALØ
      SUBRØUTINE NCALØ
C        NCAL FØR ØRIENTATIØN PRØGRAM
C        CØMPUTE IMAGE INTENSIFIER CALIBRATIØN CØEFFICIENTS
C        5TH DEGREE GENERAL  PØLYNØMIAL
C        USING MATCHING SETS ØF  CALIBRATIØN AND MEAS. CØØRDINATES
C        CALIBRATED CØØRDINATES IN (XC,YC)
C        MEASURED CØØRDINATES IN (X,Y)
C        INTERNAL CØMPUTATIØN IN M. M.
C
      CØMMØN /BLKØ/ NX,NTYPE,DX(36),DY(36),DXØ(36),DYØ(36)
      CØMMØN /BLKS/ KPT(501),X(501),Y(501),XC(501),YC(501),KRJ(501)
      DIMENSIØN WN(1296),SN(1296),KHEDR(20),CX(36),CY(36),WX(36),
     1 WY(36),B(36)
      CØMMØN WN,SN,KHEDR,CX,CY,WX,WY,XPI,YPI
C          FØRMAT STATEMENTS
    1 FØRMAT(1H1)
    2 FØRMAT(2E16.8)
    3 FØRMAT(5I5)
    4 FØRMAT(1X,I5,2X,F9.4,1X,F9.4,2X,F9.4,1X,F9.4,3X,F9.4,1X,F9.4,2X,F6
     *.1,A1,F6.1,A1,3X, F8.1,F8.1,A1,F8.1,A1)
    5 FØRMAT(I5,2F10.4,2F8.1)
    6 FØRMAT(I5,2F10.4,2F8.1)
    7 FØRMAT(/)
    8 FØRMAT(1H1,1X,5HPØINT,4X5HX-CAL,5X5HY-CAL,7X5HX-ØBS,5X5HY-ØBS,
     1   6X6HX-CØMP,4X6HY-CØMP,6X2HVX,5X2HVY,7X5HRDIST,2X6HRADIAL,
     2    3X5HTANG./)
    9 FØRMAT(/18H NØ. TERMS USED =    I3/ 20H NØ. PØINTS USED =  I4//)
   10 FØRMAT(2I5,5E16.8,2F12.3)
   11 FØRMAT(/22H CØMPUTED CØEFFICIENTS    /)
   12 FØRMAT(20A4)
   14 FØRMAT(/14H MEAN ERRØR =  F8.1/)
   15 FØRMAT(24H X-DEGREES ØF FREEDØM = F6.0/  24H Y-DEGREES ØF FREEDØM
     1= F6.0/  24H         -X- MEAN ERRØR = F8.2/   24H         -Y- MEAN ERR
     2ØR = F8.2//)
   16 FØRMAT(/22H DEGREES ØF FREEDØM = F6.0 /)
C        START
      DATA KASTR,KBLNK/1H*,1H /
      LCR=5
      LPR=6
      RLMT=25.
      NXX=NX*NX
      RLMT2 = RLMT*RLMT
      XX = NX
      DØF =     -(XX+XX)
      SWME = 0.
```

```
      SF3=1000.
C     SET REF. MATRICES TO ZERO
      CALL CLEAR (WN,NXX)
      CALL CLEAR (WX,NX)
      CALL CLEAR (WY,NX)
   40 CONTINUE
C         SET-UP INPUT DATA
      DO 45 L=1,501
      IF(KPT(L)) 46,44,43
   43 CONTINUE
      XC(L) = X(L) + XC(L)/SF3
      YC(L) = Y(L) + YC(L)/SF3
      KRJ(L) = 1
      IF(X(L)**2 + Y(L)**2 - RLMT2) 45,45,44
   44 KRJ(L) = 0
   45 CONTINUE
   46 CONTINUE
      IF(L .LE. NX) GO TO 200
      L = L-1
      NREJS = 0
      KITER = 0
      WME = 50.
   49 CONTINUE
      CALL CLEAR (CX,NX)
      CALL CLEAR (CY,NX)
      CALL CLEAR(SN,NXX)
      KTEST = 0
      KFLAG = 0
      WSQR = (3.0*WME)**2
C     COMPUTE NORMAL EQUATIONS AND DEGREES OF FREEDOM
      DO 75 K=1,L
      IF(KRJ(K)) 75,75,71
   71 CONTINUE
C     COMPUTE B(I) MATRIX
      B(1) = 1.
      B(2) = X(K)
      B(3) = Y(K)
      B(4) = X(K)*Y(K)
      B(5) = X(K)*X(K)
      B(6) = Y(K)*Y(K)
      B(7) = B(5)*Y(K)
      B(8) = B(6)*X(K)
      B(9) = B(5)*X(K)
      B(10)= B(6)*Y(K)
      IF (NX .LE. 10) GO TO 79
      B(11)= B(9)*Y(K)
      B(12)= B(10)*X(K)
      B(13)= B(7)*Y(K)
      B(14)= B(9)*X(K)
```

```
      B(15)= B(10)*Y(K)
      IF (NX .LE. 15) GO TO 79
      B(16)= B(14)*Y(K)
      B(17)= B(15)*X(K)
      B(18)= B(10)*X(K)*X(K)
      B(19)= B(9)*Y(K)*Y(K)
      B(20)= B(14)*X(K)
      B(21)= B(15)*Y(K)
      IF (NX .LE. 21) GO TO 79
      B(22)= B(20)*Y(K)
      B(23)= B(21)*X(K)
      B(24)= B(14)*B(6)
      B(25)= B(5)*B(15)
      B(26)= B(9)*B(10)
      B(27)= B(20)*X(K)
      B(28)= B(21)*Y(K)
      IF (NX .LE. 28) GO TO 79
      B(29)= B(27)*Y(K)
      B(30)= B(28)*X(K)
      B(31)= B(20)*B(6)
      B(32)= B(21)*B(5)
      B(33)= B(14)*B(10)
      B(34)= B(9)*B(15)
      B(35)= B(27)*X(K)
      B(36)= B(28)*Y(K)
   79 CONTINUE
      XD    = XC(K)
      YD    = YC(K)
      CALL MATMPY(B,1,NX,B,1,NX,SN,1,1)
      CALL MATMPY(B,1,NX,XD,1,1,CX,1,1)
      CALL MATMPY(B,1,NX,YD,1,1,CY,1,1)
   75 CONTINUE
C     SET UP XN AND YN  AND INVERT
      CALL MATINV(SN,NX,NX,SN)
      CALL MATMPY(SN,NX,NX,CX,NX,1,DX,0,0)
      CALL MATMPY(SN,NX,NX,CY,NX,1,DY,0,0)
C     COMPUTE AND PRINT RESIDUALS
C        RETURN FOR FINAL RESIDUAL COMPUTATION
   90 CONTINUE
      WVX = 0.
      WVY = 0.
      XX=NX
      DOFX = -XX
      DOFY = -XX
      DO 95 K=1,L
      B(1) =1.
      B(2) =X(K)
      B(3) =Y(K)
      B(4) =X(K)*Y(K)
```

```
      B(5) =X(K)*X(K)
      B(6) =Y(K)*Y(K)
      B(7) = B(5)*Y(K)
      B(8) = B(6)*X(K)
      B(9) = B(5)*X(K)
      B(10)= B(6)*Y(K)
      IF (NX .LE. 10) GØ TØ 99
      B(11)= B(9)*Y(K)
      B(12)= B(10)*X(K)
      B(13)= B(7)*Y(K)
      B(14)= B(9)*X(K)
      B(15)= B(10)*Y(K)
      IF (NX .LE. 15) GØ TØ 99
      B(16)= B(14)*Y(K)
      B(17)= B(15)*X(K)
      B(18)= B(10)*X(K)*X(K)
      B(19)= B(9)*Y(K)*Y(K)
      B(20)= B(14)*X(K)
      B(21)= B(15)*Y(K)
      IF (NX .LE. 21) GØ TØ 99
      B(22)= B(20)*Y(K)
      B(23)= B(21)*X(K)
      B(24)= B(14)*B(6)
      B(25)= B(5)*B(15)
      B(26)= B(9)*B(10)
      B(27)= B(20)*X(K)
      B(28)= B(21)*Y(K)
      IF (NX .LE. 28) GØ TØ 99
      B(29)= B(27)*Y(K)
      B(30)= B(28)*X(K)
      B(31)= B(20)*B(6)
      B(32)= B(21)*B(5)
      B(33)= B(14)*B(10)
      B(34)= B(9)*B(15)
      B(35)= B(27)*X(K)
      B(36)= B(28)*Y(K)
   99 CØNTINUE
      CALL MATMPY(B,1,NX,DX,NX,1,XPI,0,0)
      CALL MATMPY(B,1,NX,DY,NX,1,YPI,0,0)
      VX =(XC(K)-XPI    )*SF3
      VY =(YC(K)-YPI    )*SF3
      IF(KTEST) 50,50,56
   50 CØNTINUE
      VSQR=VX**2 + VY**2
C         MAKE REJECTIØN ØR RESTØRATIØN
      IF(KRJ(K)) 51,51,53
   51 IF(VSQR-WSQR) 52,52,56
C         RESTØRE
   52 KRJ(K)=1
```

```
      NREJS=NREJS-1
      KFLAG=1
      GØ TØ 56
   53 CØNTINUE
      IF(VSQR-WSQR) 56,56,54
C        REJECT
   54 KRJ(K)=0
      NREJS=NREJS+1
      KFLAG=1
   56 CØNTINUE
C        ACCUMULATE RMS AND DEG. ØF FREEDØM
      IF(KRJ(K)) 62,62,64
   62 CØNTINUE
      KX = KASTR
      KY = KASTR
      GØ TØ 65
   64 CØNTINUE
      KX=KBLNK
      KY=KBLNK
      DØFX = DØFX + 1.
      DØFY = DØFY + 1.
      WVX=WVX+VX*VX
      WVY=WVY+VY*VY
   65 CØNTINUE
C       PRINT RESIDUALS IF KTEST = 1
      IF(KTEST) 95,95,91
   91 CØNTINUE
      RDIST = SQRT(XPI**2 + YPI**2)
      VRC = (YPI*VY + XPI*VX)/RDIST
      VTC = (XPI*VY - YPI*VX)/RDIST
      WRITE (LPR, 4)KPT(K),XC(K),YC(K),X(K),Y(K),XPI,YPI,VX,KX,VY,KX,
     1    RDIST,VRC,KX,VTC,KX
      IF(KRJ(K)) 95,95,92
   92 CØNTINUE
      SWME = SWME + VX**2+VY**2
      DØF = DØF + 2.
      XD    = XC(K)
      YD    = YC(K)
      CALL MATMPY(B,1,NX,B,1,NX,WN,1,1)
      CALL MATMPY(B,1,NX,XD,1,1,WX,1,1)
      CALL MATMPY(B,1,NX,YD,1,1,WY,1,1)
   95 CØNTINUE
      WMEX= SQRT(WVX/DØFX)
      WMEY= SQRT(WVY/DØFY)
      WME = SQRT((WVX+WVY)/(DØFX+DØFY))
      IF(KTEST) 89,89,88
   88 CØNTINUE
      WRITE (LPR, 7)
      WRITE(LPR,12) KHEDR
```

```
      WRITE(LPR,9) NX,L
      WRITE (LPR, 7)
      WRITE (LPR, 15)DØFX,DØFY,WMEX,WMEY
      WRITE(LPR,14) WME
      WRITE(LPR,7)
   89 CØNTINUE
      KITER=KITER+1
      GØ TØ (93,96,96,97,97),KITER
   93 CØNTINUE
      GØ TØ 49
   96 CØNTINUE
      IF(KFLAG) 97,97,49
   97 CØNTINUE
      IF(KTEST) 98,98,100
   98 CØNTINUE
      KTEST = 1
      WRITE (LPR, 8)
      GØ TØ 90
C         FINAL PRØCESSING FØR ALL FRAMES
  100 CØNTINUE
      WRITE(LPR, 1)
      WRITE(LPR,12) KHEDR
       WME = SQRT(SWME/DØF)
      WRITE(LPR,16) DØF
      WRITE(LPR,14) WME
      CALL MATINV(WN,NX,NX,SN)
      CALL MATMPY(SN,NX,NX,WX,NX,1,DX,0,C)
      CALL MATMPY(SN,NX,NX,WY,NX,1,DY,0,C)
      WRITE(LPR,11)
      NPX=NX+1
      N=0
      DØ 105 M=1,NXX,NPX
      N=N+1
      TA=SQRT(SN(M)) * WME/1000.
      TB=DX(N)/TA
      TC=DY(N)/TA
      WRITE(LPR,10) N,M,DX(N),DY(N),CX(N),CY(N),TA,TB,TC
  105 CØNTINUE
  200 CØNTINUE
      RETURN
      END
```

4.4 General Subroutines

4.4.1 Introduction

Three general subroutines CLEAR, MATMPY, and MATINV were used in this set of programs. The function and listings of these subroutines are included for reference only.

4.4.2 Subroutine CLEAR

Subroutine CLEAR set (N) elements of a real array (X) to zero.

```
C
      SUBRØUTINE CLEAR(X,N)
C        CLEAR STØRAGE TØ ZERØ
      DIMENSIØN X(1)
      DØ 1 I=1,N
    1 X(I) = 0.
      RETURN
      END
```

4.4.3 Subroutine MATMPY

Subroutine MATMPY multiplies a matrix B with dimensions of NRB rows and NCB columns by matrix A with dimensions of NRA rows and NCA columns and stores the results in C. Codes for optional multiplications and accumulations are given in the listing.

```
C
      SUBRØUTINE MATMPY(A,NRA,NCA,B,NRB,NCB,C,M1,M2)
C
C  MATMPY   A FØRTRAN MATRIX MULTIPLY (AND ADD) PACKAGE
C     WILL HANDLE ARRAYS ØF ANY DIMENSIØNS
C     NØ CHECK IS MADE TØ ENSURE A VALID PRØDUCT ØR SUM.
C
CØDES FØR ØPTIØNAL MULTIPLIES AND ADDITIØNS
C
C        M1           R          M2          C
C         0           A*B         0          R
C         1          AT*B         1          C + R
C         2          A*BT        -1          C - R
C         3         AT*BT        -2          -R
C
      DIMENSIØN      A(1),    B(1),   C(1)
      IF(M1-1) 40,50,10
   10 NCC = NRB
      INR = NCB
      MB = 1
      INCB = NRB
      IF(M1-2) 50,30,20
   20 NRC = NCA
      INCA = 1
      MA = NRA
      GØ TØ 60
   30 NRC = NRA
      INCA = NRA
      MA = 1
      GØ TØ 60
   40 NRC = NRA
      NCC = NCB
      MA = 1
      MB = NRB
      INR = NCA
      INCA = NRA
      INCB = 1
      GØ TØ 60
   50 NRC = NCA
      NCC = NCB
      INR = NRA
      MA = NRA
      MB = NRB
      INCA = 1
      INCB = 1
C
```

```
C               POSITIVE          NEGATIVE
C     MR         RP=R               RP=-R
C     MC         C=C+RP             C=RP
C
   60 IF(M2) 70,80,90
   70 IF(M2+1) 110,100,80
   80 MC=-1
      MR = 1
      GO TO 120
   90 MC = 1
      MR = 1
      GO TO 120
  100 MC = 1
      MR = -1
      GO TO 120
  110 MC = -1
      MR = -1
  120 CONTINUE
      DO 190 I=1,NRC
      IJ = I
      INTLA = (I-1)*MA + 1
      DO 180 J=1,NCC
      R= 0.
      IB = (J-1)*MB + 1
      IA = INTLA
      DO 130  K=1,INR
      R = R + A(IA)*B(IB)
      IA = IA + INCA
      IB = IB + INCB
  130 CONTINUE
      IF(MR) 140,140,150
  140 R= -R
  150 IF(MC) 160,160,170
  160 C(IJ)=  R
      GO TO 180
  170 C(IJ) =  C(IJ) + R
  180 IJ = IJ + NRC
  190 CONTINUE
      RETURN
      END
```

4.4.4 Subroutine MATINV

Subroutine MATINV inverts a matrix with dimensions of NROW rows and NCOL columns and stores the inverse matrix in B. A and B may be the same array.

```
C
      SUBRØUTINE MATINV (A,NRØW,NCØL,B)
      DIMENSIØN A(1),B(1)
      NR=NRØW
      NC=NCØL
      NA=NR*NC
      DØ 5 I=1,NA
    5 B(I)=A(I)
      DØ 25 I=1,NR
      N=I+NR*(I-1)
      C=1.0/B(N)
      B(N)=1.0
      DØ 10 N=I,NA,NR
   10 B(N)=C*B(N)
      DØ 25 K=1,NR
      N=K+NR*(I-1)
      IF (I-K)15,25,15
   15 C=B(N)
      B(N)=0.0
      DØ 20 J=1,NC
      L=NR*(J-1)
      N=K+L
      L=I+L
   20 B(N)=B(N)-C*B(L)
   25 CØNTINUE
      RETURN
      END
```

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