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Final Report

# PERFORMANCE ANALYSIS OF THE PHOTOGRAMMETRIC SYSTEM USED FOR CALIBRATION OF ASFIR

Dean C. Merchant
Syracuse University Research Corporation

TECHNICAL REPORT NO. RADC-TR- 66-653
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Rome Air Development Center
Research and Technology Division
Air Force Systems Command
Griffiss Air Force Base, New York

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## FOREWORD

This final report was prepared by Syracuse University Research Corporation, Syracuse, New York, under Contract AF30(602)-3438, Project 6512.

RADC Project Engineer was Charles A. Ballou, Jr., EMASI.

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This technical report has been reviewed and is approved.

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ABSTRACT

A photogrammetric resection technique is used as a basis for the initial calibration of a ground based radar (ASFIR). An analysis of the influences of errors in camera calibration and geodetic bias is developed. The errors in range and azimuth from the ground stations to the aircraft are computed using the results from a stellar calibration performed on the camera. The results confirm earlier predictions that the photogrammetric error contribution to error in range (standard error) amounts to about 1 part in 10,000 of the flying height along each coordinate axis. This error is to be augmented with the geodetic bias error estimated to be ± 1 meter at 400 kilometers.

TABLE OF CONTENTS



List of Figures



List of Tables

## EVALUATION

We have developed in the house a radar evaluation system for use in determining the tracking accuracy of radars when tracking aircraft type targets. This system uses a standard KC-1 camera, accurately controlled ground surveys and photogrammetric resection techniques. This report, the fourth in series of reports describing the system, consists of an error analysis of the system as used in the ASFIR evaluation configuration. The results indicate the system is sufficiently accurate to permit evaluation of the bias errors in ASFIR and is extremely good in evaluating angular accuracy.

DONALD I. ZULCH
Project Engineer

## SECTION I

## INTRODUCTION

The Rome Air Development Center (RADC) has been engaged in the development of the "Active Swept Frequency Interferometer Radar" (ASFIR) system. A photogrammetric resection technique is currently employed to provide a basis of calibration and evaluation of the ASFIR system.[1] The method of resection provides a means for determining the spatial rectangular coordinates of a target aircraft operating up to one hundred miles from the radar ground stations.

The primary purpose of this report is to present the results of a study of the influences of geodetic and photogrammetric errors upon the measures of range and azimuth to the target aircraft. Details pertinent to other aspects of this technique such as camera installation[6], description of control ranges[2,7] and results of a stellar camera calibration[4] may be found in other recent publications.

Due to delays in the development and modification of a KC-1 camera to meet the stringent requirements of the ASFIR calibration system, an interim camera system has been suggested and used in the ASFIR program. The interim camera is a KC-1B calibrated against a star background on photography taken through the photographic window. Film shrinkage is compensated by use of a glass grid (1 cm interval) flashed on the unexposed film before loading it into the camera magazine. The latent image of the grid (reseau) is processed together with the imagery of the control field. Studies have indicated that shrinkage is compensated to approximately ± 2 microns (std error) by this means.[8]

This report presents the theoretical developments necessary for studying the propagation of the camera calibration errors and photo coordinate measurement errors through the photogrammetric resection procedure. The influence of these errors on the ASFIR calibration system errors in range and azimuth is also developed. The report concludes with an analysis of the results of the camera calibration and their influences on the measurements of ASFIR target range and azimuth. The interim camera system is treated exclusively.

## SECTION II

## CALIBRATION AND ANALYSIS OF RESULTS

### A. Camera Calibration

The initial study of the use of a photogrammetric resection to establish the target coordinates for the ASFIR program at RADC[1] depended on an estimate of the accuracy of the photographic system. The camera performance to achieve the target aircraft location to the necessary accuracy indicated that more than the usual laboratory calibration would be necessary.

Ideally, the photographic system should be calibrated under the same circumstances in which it will be used. This would mean that for calibration, photography should be used which has been taken over a control range at the same altitude, using the same film, filter, magazine and window that will be used operationally for the ASFIR tests.

After some investigation, it was concluded that neither government nor private agencies currently had an adequate operational total airborne calibration procedure. One author had concluded, however, that such a calibration was a logical extension of their established procedures.[3]

Rather than undergo further development to obtain a total photographic system calibration for the ASFIR application, it was decided that a calibration based on use of stars as a control field would be a satisfactory compromise. Accordingly, a contract was arranged between RADC and Autometrics Corp. (Raytheon) in which they would perform a calibration according to the Stellar method based on the distortion model of Brown.[3] The results of the calibration were presented in the "Final Engineering Report" from Autometrics on September 7, 1965.[4]

B. Analysis of Errors

In the final analysis, it is the calibration system error in range and azimuth that is of concern for purposes of evaluation of the ASFIR system. The problem then is that of propagating the errors in calibration of the camera coupled with photo coordinate measurement errors which occur during any subsequent photogrammetric resection into the errors in the spatial coordinates of the exposure station. These errors in turn must be propagated into errors in range and azimuth from the ASFIR master to the exposure station.

1. Derivations

The relationships between photo coordinates and elements of single camera exterior orientation have been derived in numerous publications.[5] Assuming a right-handed rectangular coordinate system for both survey control and photo coordinates and assuming that all camera rotations are right handed, the following equations result. (Assume $\omega$ as the primary, $\phi$ the secondary and k the tertiary rotation.)

$$(1a)\quad x_i = x_o + c \left[ \frac{(X_i - X_o)\cos\phi\cos k + (Y_i - Y_o)(\cos\omega\sin k + \sin\omega\sin\phi\cos k) + (Z_i - Z_o)(\sin\omega\sin k - \cos\omega\ \sin\phi\cos k)}{(X - X_o)\sin\phi - (Y - Y_o)(\sin\omega\ \cos\phi) + (Z - Z_o)(\cos\omega\ \cos\phi)} \right]$$

$$(1b)\quad y_i = y_o + c \left[ \frac{-(X - X_o)\cos\phi\sin k + (Y_i - Y_o)(\cos\omega\ \cos k - \sin\omega\ \sin\phi\sin k) + (Z_i - Z_o)(\sin\omega\ \cos k + \cos\omega\ \sin\phi\sin k)}{(X_i - X_o)\sin\phi - (Y_i - Y_o)(\sin\omega\ \cos\phi) + (Z_i - Z_o)\cos\omega\ \cos\phi} \right]$$

where:

| | | |
|---|---|---|
| $X_i, Y_i, Z_i$ | ~ | survey coordinates of control point (i) |
| $X_o, Y_o, Z_o$ | ~ | survey coordinates of the exposure station |
| $k, \phi, \omega$ | ~ | camera rotations |
| $x_o, y_o, c$ | ~ | coordinates of principle point in a fiducial center origin system and the calibrated focal length |

For purposes of a "Least Squares Adjustment", the equations (1a) and (1b) are put into linear form with respect to the six exterior orientation elements by use of Taylor's Series neglecting second and higher order terms. The derivative of each equation with respect to each of the six elements is taken individually for this purpose. By assuming verticality after differentiation, a great simplification is accomplished without loss of value in the analysis of propagation of the system errors. Equation (1a) and (1b) after linearization followed by simplification due to assumed verticality become:

$$(1c) \quad \Delta \bar{x}_i = -\frac{c}{Z_i - Z_o} \Delta X_o + 0 \; \Delta Y_o + c \frac{X_i - X_o}{(Z_i - Z_o)^2} = \Delta Z_o + \frac{c}{Z_i - Z_o} (Y_i - Y_o) \; \Delta k - c\left(1 + \frac{(X_i - X_o)^2}{(Z_i - Z_o)^2}\right) \Delta \phi + \frac{c(X_i - X_o)}{(Z_i - Z_o)^2} (Y_i - Y_o) \; \Delta \omega$$

$$(1d) \quad \Delta \bar{y}_i = + 0 \; \Delta X_o - \frac{c}{Z_i - Z_o} \Delta Y_o + c \frac{(Y_i - Y_o)}{(Z_i - Z_o)^2} \Delta Z_o - \frac{c}{Z_i - Z_o} (X_i - X_o) \; \Delta k - \frac{c(Y_i - Y_o)}{(Z_i - Z_o)^2} (X_i - X_o) \; \Delta \phi + c\left(1 + \frac{(Y_i - Y_o)^2}{(Z_i - Z_o)^2}\right) \Delta \omega$$

The altered photo coordinates $(x_i, y_i)$ in equations (1) computed from measured photo coordinates $(x_i, y_i)$ which have been previously corrected for refraction and shrinkage are obtained by means of Brown's model[3] for interior orientation. The altered photo coordinates $(x_i, y_i)$ are expressed by equations (2):

$$\text{(2a)} \quad x_i = (1 + K1\, R^2 + K2\, R^4 + K3\, R^6)\,(\bar{x}_i - x_o) - (J1\, R^2 + J2\, R^4)\sin\phi$$

$$\text{(2b)} \quad y_i = (1 + K1\, R^2 + K2\, R^4 + K3\, R^6)\,(\bar{y}_i - y_o) + (J1\, R^2 + J2\, R^4)\cos\phi$$

where:

| | | |
|---|---|---|
| K1, K2, K3 | ~ | coefficients of radial symmetrical distortion |
| J1, J2, $\phi$ | ~ | coefficients of asymetric distortion |
| $x_o$, $y_o$ | ~ | photo coordinates of principle point |
| $\bar{x}_i$, $\bar{y}_i$ | ~ | photo coordinates of point (i) corrected only for refraction and film shrinkage |

$$R^2 = \bar{x}_i^{\,2} + \bar{y}_i^{\,2}$$

Equations (2) may be rewritten in terms of measured photo coordinates $(\bar{x}_i, \bar{y}_i)$ as a function of the elements of interior orientation.

$$\text{(3a)} \quad \bar{x}_i = \left\{ x_i + (J1\, R^2 + J2\, R^4)\sin\phi \right\} \cdot \left[ 1 + K1\, R^2 + K2\, R^4 + K3\, R^6 \right]^{-1} + x_o$$

(3b) $\bar{y}_i = \left\{ y_i - (J1\ R^2 + J2\ R^4) \cos\phi \right\} \cdot \left[ 1 + K1\ R^2 + K2\ R^4 + K3\ R^6 \right]^{-1} + y_o$

It is intended that the final results be in terms of estimated errors in range and azimuth from the ASFIR master to the target aircraft. The relationships between exposure station coordinates ($X_o$, $Y_o$, $Z_o$) and the coordinates of the ASFIR master in terms of range and azimuth are evidently as follow:

For Range: (D)

(4) $D = \left[ (X_o - X_m)^2 + (Y_o - Y_m)^2 + (Z_o - Z_m)^2 \right]^{1/2}$

For Azimuth: ($\theta$)

With reference to Figure 1 shown on the following page.

For purposes of error analysis, the influence of errors in $X_o$ and $Z_o$ on the computation of azimuth are negligible provided the angle ($\theta$) at the master station is close to $90^o$. For other values of ($\theta$), the $X_o$ and $Y_o$ errors both will influence the error of ($\theta$). However, the magnitude of the ($\theta$) error will be approximately unchanged. Introducing this simplification, the influence of errors in coordinates of the target on the azimuth angle ($\theta$) as established at the ASFIR master station is:

(5a) $\partial \theta / \partial X_o = 0$

(5b) $\partial \theta / \partial Y_o = 1/D$

(5c) $\partial \theta / \partial Z_o = 0.$

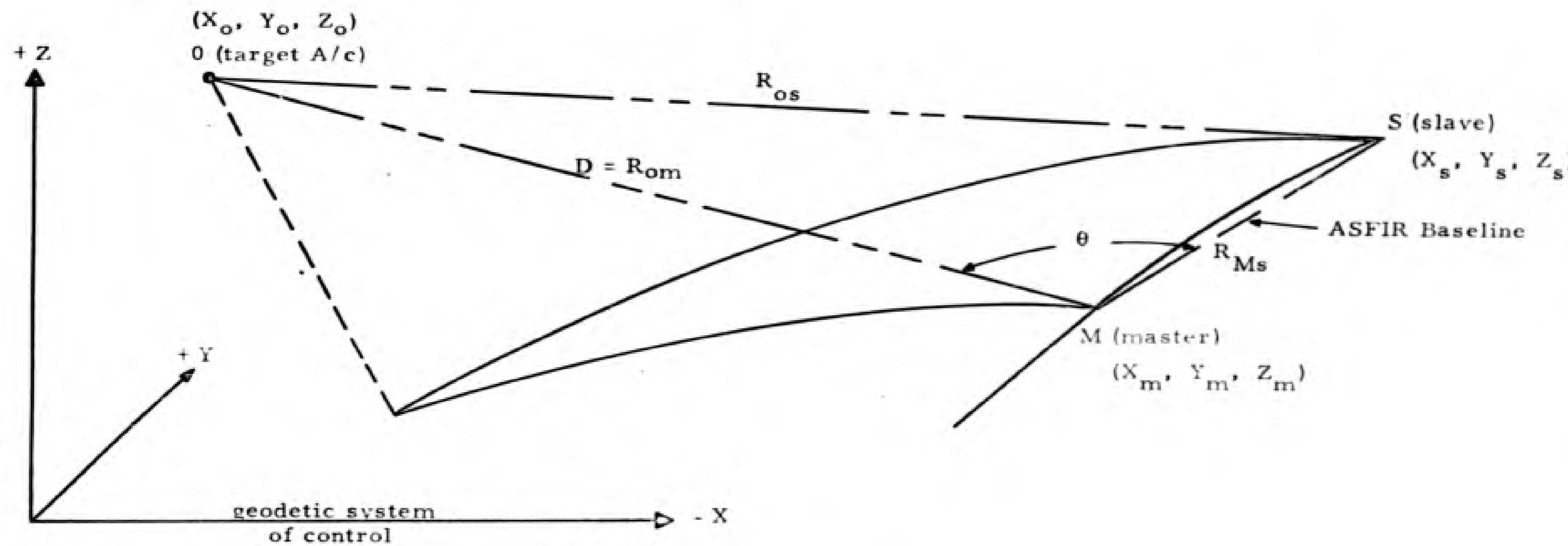


Figure 1: Geometric Relations Between Target and ASFIR Baseline

## 2. Propagation of Errors

The estimated errors in the elements of interior orientation of the camera resulting from the star calibration combined with estimated future photo coordinate measurement errors may be expressed in terms of their influence on the final range and azimuth by application of the "general law of error propagation". This may be conveniently treated by matrix notation.

Beginning with the results of the Stellar calibration in terms of the covariance matrix of the elements of the calibration ($\sum_c$), the estimated influence on the photo coordinates may be computed.

$$\sum_{xy} = F^T \sum_c F$$

where:

$\sum_{xy}$ ~ variance covariance of photo coordinates due only to estimated errors in the camera calibration.

$$F = \begin{bmatrix} \cdots \partial \bar{x}_i / \partial x_o & \cdots \partial \bar{y}_i / \partial x_o & \cdots \\ \vdots & \vdots & \\ \cdots \partial \bar{x}_i / \partial \phi & \cdots \partial \bar{y}_i / \partial \phi & \cdots \end{bmatrix}_{9 \times 2n}$$

n ~ number of survey control points employed

In addition to the camera calibration errors, the errors of photo coordinate measurement made during analysis of results of the photogrammetric resection in conjunction with operation with the ASFIR system must be considered. It is assumed that photo coordinates are measured directly on a rectangular (x, y) coordinate comparator. Consequently, no correlation between measured photo coordinates is considered. The combined covariance of photo coordinates considering both calibration errors and subsequent photo measurement errors is then:

$$\sum_{axy} = \sum_{xy} + \sum_{p}$$

where:

$$\sum_{p} = \begin{bmatrix} \sigma_{\bar{x}_i}^{2} & 0 \\ 0 & \sigma_{\bar{y}_i}^{2} \end{bmatrix}_{2 \times 2}$$

The influence of the combined estimated photo coordinate errors on exposure station coordinates ($X_o$, $Y_o$, $Z_o$) may now be computed. The photogrammetric resection employed to determine the exposure station coordinates ($X_o$, $Y_o$, $Z_o$) requires an adjustment computation due to the redundancy of photo coordinates in excess of the six unknown parameters of exterior camera orientation. Further, the results of this adjustment will be influenced by the number and location of the given ground control points appearing on the photo. For the purposes of this analysis, five points will be used located as shown in Figure 2.

The method of propagation through a least squares adjustment of the errors in the observations has been demonstrated by D. Brown.[5]

$$\Sigma_{axy}^{o} = \frac{\Sigma_{axy}}{\sigma_o^2}$$

where:

$\sigma_o^2$ ~ unit variance arbitrarily chosen

$\Sigma_{axy}^{o}$ ~ relative covariance on the observations

The relative weights of the observed photo coordinates will be taken as:

$$P = \Sigma_{axy}^{o\,-1}$$

The coefficient matrix of the normal equations (N) may then be developed as:

$$N = A^T PA$$

where:

$$A = \begin{bmatrix} \partial x_i/\partial X_o & \partial x_i/\partial Y_o & \partial x_i/\partial Z_o & \partial x_i/\partial k & \partial x_i/\partial \phi & \partial x_i/\partial \omega \\ \hline \partial y_i/\partial X_o & \partial y_i/\partial Y_o & \partial y_i/\partial Z_o & \partial y_i/\partial k & \partial y_i/\partial \phi & \partial y_i/\partial \omega \end{bmatrix}_{2n \times 6}$$

where:

$i \rightarrow 1$ to $n$

$n$ ~ number of photo or control points

$X_o$, $Y_o$, $Z_o$, $k$, $\phi$, $\omega$ ~ elements of single photo exterior orientation

The covariance matrix on the adjusted elements of exterior orientation is then:

$$\Sigma_E = \sigma_o^2 \cdot N^{-1}$$

The estimated covariance matrix on the spatial coordinates may be extracted as the first 3 x 3 block of elements in the upper left corner of the $\sum_E$ matrix.

i. e.,

$$\sum_{xyz} = \begin{bmatrix} \sigma_{x_o}^2 & \sigma_{x_o y_o} & \sigma_{x_o z_o} \\ \sigma_{x_o y_o} & \sigma_{y_o}^2 & \sigma_{y_o z_o} \\ \sigma_{x_o z_o} & \sigma_{y_o z_o} & \sigma_{z_o}^2 \end{bmatrix}$$

Finally, the influence of calibration errors and photo coordinate errors on range (D) and azimuth ($\theta$) between the ASFIR master station and the target aircraft (exposure station) may be computed ($\sum_{D\theta}$).

$$\sum_{D\theta} = H^T \cdot \sum_{xyz} \cdot H$$

where:

$$H = \begin{bmatrix} \partial D/\partial X_o & \partial \theta/\partial X_o \\ \partial D/\partial Y_o & \partial \theta/\partial Y_o \\ \partial D/\partial Z_o & \partial \theta/\partial Z_o \end{bmatrix}$$

3. Sample Computations of Photogrammetric Errors

The influence of the camera calibration errors on range and azimuth to the target aircraft coupled with the predicted errors due to subsequent photo coordinate measurements are computed according to the procedure developed above. The procedure is programmed for digital computation. Several combinations of range, altitude and photo coordinate standard errors are used as test data.

For each combination or case, a fixed pattern of "errorless" ground control points is used. Figure 2 on page 15a indicates the control point pattern.

## 3.1 Results from Stellar Calibration

Upon special request by RADC, the Autometrics Corporation supplied the inverse coefficient matrix and unit variance resulting from the stellar calibration adjustment computation performed on the data from the ASFIR KC-1 camera. The terms of the inverse corresponding to the elements of interior orientation are extracted for use in the following error propagation computations. The inverse corresponding to the interior elements of orientation of the camera is broken into two sections and is presented in Table 3.1 with appropriate marginal notation.

Table 3.1 ($N^{-1}$) Elements of Inverse Coefficient Matrix

| $\Delta x_o$ | $\Delta y_o$ | $\Delta c$ | $\Delta K1$ | $\Delta K2$ |
|---|---|---|---|---|
| .3676E-05 | .7008E-07 | -.8000E-07 | .3783E-12 | -.1058E-15 |
| .7009E-07 | .4514E-05 | -.2275E-06 | .1268E-11 | -.1636E-15 |
| .8000E-07 | -.2275E-06 | .1211E-04 | -.2807E-10 | .2815E-14 |
| .3783E-12 | .1268E-11 | -.2807E-10 | .7556E-16 | -.8229E-20 |
| .1058E-15 | -.1636E-15 | .2815E-14 | -.8229E-20 | .9481E-24 |
| .4974E-20 | .7698E-20 | -.8453E-19 | .2602E-24 | -.3114E-28 |
| .1465E-10 | -.1945E-10 | .7151E-11 | -.4189E-16 | .9778E-20 |
| .5628E-14 | .1619E-14 | -.1013E-14 | .2596E-20 | -.5467E-24 |
| .6047E-04 | .5366E-04 | -.6853E-04 | .1351E-09 | -.1139E-13 |

| ΔK3 | ΔJ1 | ΔJ2 | Δφ |
|---|---|---|---|
| .4974E-20 | -.1465E-10 | .5628E-14 | .6047E-04 |
| .7698E-20 | -.1945E-10 | .1619E-14 | .5366E-04 |
| -.8453E-19 | .7151E-11 | -.1013E-14 | -.6853E-04 |
| .2602E-24 | -.4189E-16 | .2596E-20 | .1351E-09 |
| -.3114E-28 | .9778E-20 | -.5467E-24 | -.1139E-13 |
| .1052E-32 | -.4840E-24 | .2803E-28 | .2384E-18 |
| -.4840E-24 | .3849E-13 | -.2057E-17 | .1449E-08 |
| .2803E-28 | -.2057E-17 | .1330E-21 | .4045E-13 |
| .2384E-18 | .1449E-08 | .4045E-13 | .3937E-01 |

The unit variance of the calibration is given as ($\pm$ 7.25086). The covariance matrix on the elements of camera calibration is then:

$$\sum_c = \pm 7.25086 \, . \, N^{-1}$$

3.2 <u>Covariance of Photo Coordinates Estimated from the Stellar Calibration Results</u>

Using the five control points indicated in Figure 2 and the covariance of the interior elements, the F matrix is formed (see Section B2) and the covariance of the photo coordinates is calculated ($\sum_{xy}$).

$$\sum_{xy} = F^T \, . \, \sum_c \, . \, F$$

The covariance on the photo coordinates is broken into two parts and tabulated in Table 3.2 with appropriate marginal notation.

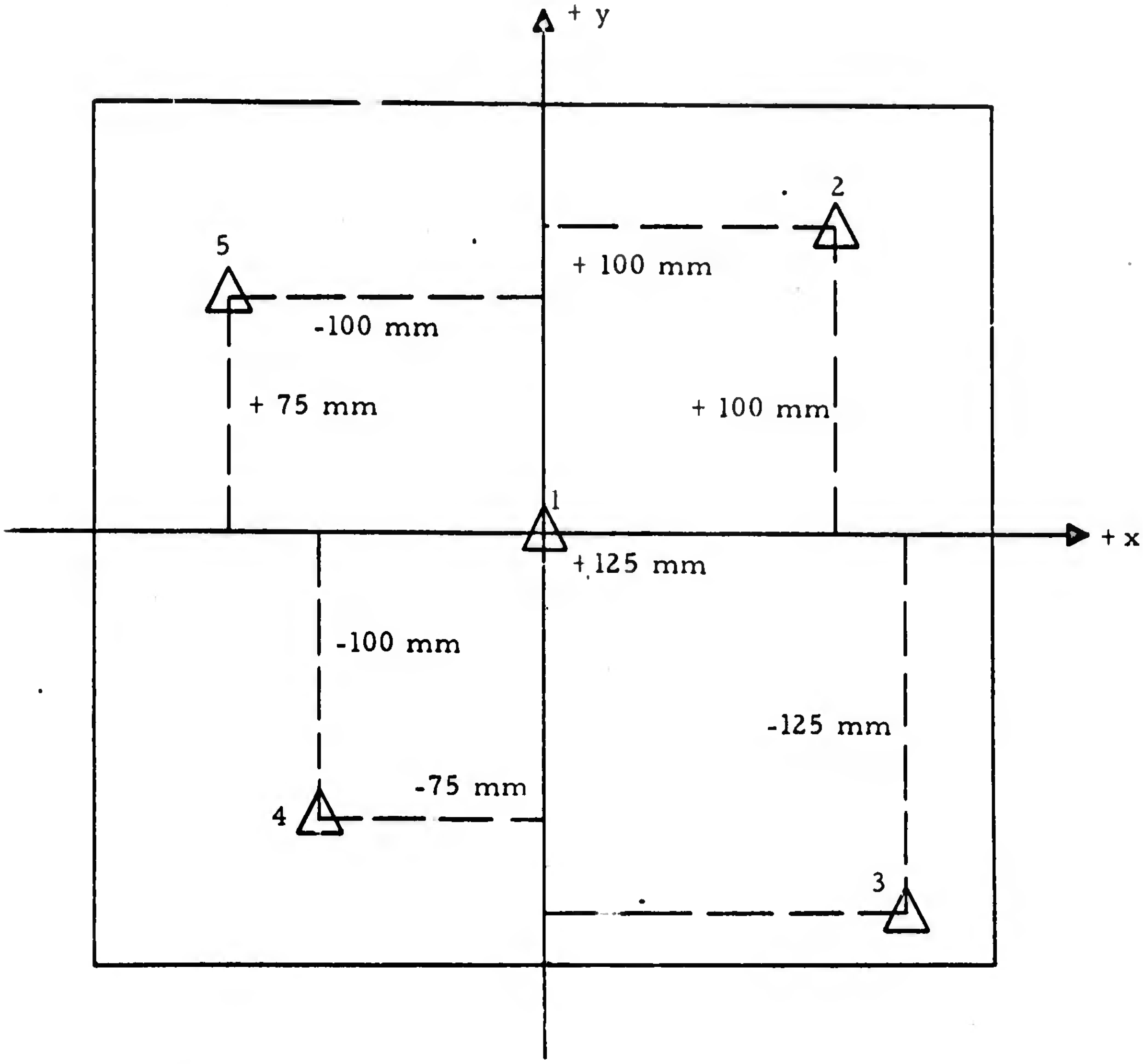


Figure 2: Arrangement of Control Point Images

Table 3.2 ($\sum_{xy}$) Covariance of Photo Coordinates

| $x_1$ | $x_2$ | $x_3$ | $x_4$ | $x_5$ |
|---|---|---|---|---|
| .266543E-04 | .370868E-04 | .806005E-05 | .350792E-04 | .349076E-04 |
| .370868E-04 | .322242E-03 | .159498E-02 | -.744106E-04 | -.962371E-04 |
| .806005E-05 | .159498E-02 | .117336E-01 | -.616286E-03 | -.719010E-03 |
| .350792E-04 | -.744107E-04 | -.616286E-03 | .142189E-03 | .155894E-03 |
| .349076E-04 | -.962368E-04 | -.719009E-03 | .155894E-03 | .171874E-03 |
| .508215E-06 | -.137042E-04 | -.964675E-04 | .757302E-05 | .925031E-05 |
| .359519E-05 | -.267235E-03 | -.163574E-02 | .151624E-03 | .175736E-03 |
| -.600546E-04 | .144929E-02 | .114707E-01 | -.719719E-03 | -.822565E-03 |
| .895329E-06 | .164026E-03 | .781451E-03 | -.103133E-03 | -.119384E-03 |
| .372998E-06 | -.148571E-03 | -.760516E-03 | .938412E-04 | .109192E-03 |

| $y_1$ | $y_2$ | $y_3$ | $y_4$ | $y_5$ |
|---|---|---|---|---|
| .508143E-06 | .359512E-05 | -.600547E-04 | .895256E-06 | .372926E-06 |
| -.137043E-04 | -.267235E-03 | .144929E-02 | .164026E-03 | -.148571E-03 |
| -.964676E-04 | -.163574E-02 | .114707E-01 | .781451E-03 | -.760515E-03 |
| .757295E-05 | .151624E-03 | -.719719E-03 | -.103133E-03 | .938410E-04 |
| .925024E-05 | .175736E-03 | -.822564E-03 | -.119384E-03 | .109192E-03 |
| .327305E-04 | .514688E-04 | -.703677E-04 | .267908E-04 | .404618E-04 |
| .514688E-04 | .345301E-03 | -.159316E-02 | -.128293E-03 | .209272E-03 |
| -.703677E-04 | -.159316E-02 | .117645E-01 | .825039E-03 | -.720679E-03 |
| .267908E-04 | -.128294E-03 | .825040E-03 | .172263E-03 | -.683563E-04 |
| .404618E-04 | .209272E-03 | -.720680E-03 | -.683565E-04 | .142195E-03 |

## 3.3 Results of Test Cases

Results are computed for each combination of two values of range and of target aircraft altitude. Each of these combinations are evaluated at three representative values of variance of photo coordinate measurement.

The values of range are 200 and 400 kilometers; the values of altitude are 10 and 30 kilometers and the photo coordinate standard errors due to measurement alone are $\pm$ 2, 5 and 10 microns.

The results of the twelve cases are presented in the following twelve pages.

```
PARAMETERS OF SAMPLE CASE
ALT 10000.000METERS
RANGE    200249.METERS
NUMBER OF CONTROL PTS.        5
WITH PHOTO COORDINATE STD ERRORS OF      .0020 MM IN X AND Y

COVARIANCE FOR EXTERIOR ORIENTATION

    XO         YO         ZO       KAPPA        PHI       OMEGA
.1792E+00-.3207E-01 .1579E-01-.8625E-06-.7777E-05 .1580E-05
.3207E-01 .2108E+00-.1817E-01 .5253E-07 .4140E-05-.5644E-05
.1579E-01-.1817E-01 .7335E+00-.1367E-05-.5343E-05 .3759E-05
.8625E-06 .5251E-07-.1367E-05 .9529E-10 .1109E-09-.1218E-10
.7777E-05 .4141E-05-.5343E-05 .1109E-09 .9974E-09-.2452E-09
.1580E-05-.5644E-05 .3759E-05-.1218E-10-.2452E-09 .5967E-09
EST. ST. ERRORS FOR EXPO. STA. IN METERS IN X  .423      IN Y  .459        IN Z  .856
COVARIANCE MATRIX ON RANGE AND AZIMUTH

  RANGE      AZIMUTH
 .1822E+00-.1645E-06
-.1645E-06 .5257E-11


STANDARD ERROR IN RANGE .4268E+00METERS
STANDARD ERROR IN AZIMUTH .2292E-05RADIANS
```

```
PARAMETERS OF SAMPLE CASE
ALT 10000.000METERS
RANGE    200249.METERS
NUMBER OF CONTROL PTS.         5
WITH PHOTO COORDINATE STD ERRORS OF      .0050 MM  IN X AND Y

COVARIANCE FOR EXTERIOR ORIENTATION

    XO          YO          ZO        KAPPA        PHI        OMEGA
.5409E+00-.1482E+00-.3835E-01-.1902E-05-.3388E-04 .1328E-04
.1482E+00 .5833E+00 .8260E-01-.1018E-06 .1151E-04-.3333E-04
.3835E-01 .8260E-01 .9366E+00-.1505E-05 .2764E-05-.5741E-05
.1902E-05-.1018E-06-.1505E-05 .4889E-09 .2703E-09-.3805E-10
.3388E-04 .1151E-04 .2764E-05 .2703E-09 .3337E-08-.1056E-08
.1328E-04-.3333E-04-.5741E-05-.3806E-10-.1056E-08 .2891E-08
EST. ST. ERRORS FOR EXPO. STA. IN METERS IN X  .735      IN Y  .763       IN Z  .967
COVARIANCE MATRIX ON RANGE AND AZIMUTH

  RANGE      AZIMUTH
 .5381E+00-.7185E-06
-.7185E-06 .1454E-10

STANDARD ERROR IN RANGE .7335E+00METERS
STANDARD ERROR IN AZIMUTH .3814E-05RADIANS
```

```
PARAMETERS OF SAMPLE CASE
ALT 10000.000METERS
RANGE   200249.METERS
NUMBER OF CONTROL PTS.          5
WITH PHOTO COORDINATE STD ERRORS OF      .0100 MM IN X AND Y

COVARIANCE FOR EXTERIOR ORIENTATION

    XO          YO          ZO        KAPPA        PHI       OMEGA
.1570E+01-.6014E+00-.2699E+00 .2287E-05-.1025E-03 .5372E-04
.6014E+00 .1858E+01 .3430E+00 .7595E-06 .3765E-04-.1294E-03
.2699E+00 .3430E+00 .1282E+01-.2207E-05 .1847E-04-.2941E-04
.2287E-05 .7595E-06-.2207E-05 .1636E-08 .1554E-10-.7503E-10
.1025E-03 .3765E-04 .1847E-04 .1554E-10 .8537E-08-.3463E-08
.5372E-04-.1294E-03-.2941E-04-.7503E-10-.3463E-08 .1066E-07
EST. ST. ERRORS FOR EXPO. STA. IN METERS IN X 1.253      IN Y 1.363        IN Z 1.132
COVARIANCE MATRIX ON RANGE AND AZIMUTH

  RANGE      AZIMUTH
 .1542E+01-.2914E-05
-.2914E-05 .4634E-10

STANDARD ERROR IN RANGE .1242E+01METERS
STANDARD ERROR IN AZIMUTH .6807E-05RADIANS
```

```
PARAMETERS OF SAMPLE CASE
  ALT 30000.000METERS
  RANGE   202237.METERS
  NUMBER OF CONTROL PTS.          5
  WITH PHOTO COORDINATE STD ERRORS OF      .0020 MM IN X AND Y

  COVARIANCE FOR EXTERIOR ORIENTATION

       XO         YO         ZO       KAPPA       PHI      OMEGA
  .1613E+01-.2886E+00 .1421E+00-.2587E-05-.2333E-04 .4741E-05
  .2886E+00 .1897E+01-.1635E+00 .1576E-06 .1242E-04-.1693E-04
  .1421E+00-.1635E+00 .6602E+01-.4101E-05-.1602E-04 .1127E-04
  .2587E-05 .1575E-06-.4101E-05 .9529E-10 .1109E-09-.1218E-10
  .2333E-04 .1242E-04-.1603E-04 .1109E-09 .9974E-09-.2452E-09
  .4741E-05-.1693E-04 .1127E-04-.1218E-10-.2452E-09 .5967E-09
  EST. ST. ERRORS FOR EXPO. STA. IN METERS IN X 1.270      IN Y 1.377      IN Z 2.569
  COVARIANCE MATRIX ON RANGE AND AZIMUTH

   RANGE     AZIMUTH
   .1764E+01-.1531E-05
  -.1531E-05 .4639E-10

  STANDARD ERROR IN RANGE .1328E+01METERS
  STANDARD ERROR IN AZIMUTH .6811E-05RADIANS
```

```
PARAMETERS OF SAMPLE CASE
 ALT 30000.000METERS
 RANGE   202237.METERS
 NUMBER OF CONTROL PTS.          5
 WITH PHOTO COORDINATE STD ERRORS OF      .0050 MM IN X AND Y

COVARIANCE FOR EXTERIOR ORIENTATION

     XO         YO         ZO       KAPPA       PHI       OMEGA
 .4868E+01-.1333E+01-.3452E+00-.5706E-05-.1016E-03 .3985E-04
 .1333E+01 .5250E+01 .7434E+00-.3054E-06 .3455E-04-.1000E-03
 .3452E+00 .7434E+00 .8430E+01-.4515E-05 .8292E-05-.1722E-04
 .5706E-05-.3054E-06-.4515E-05 .4889E-09 .2703E-09-.3806E-10
 .1016E-03 .3455E-04 .8291E-05 .2703E-09 .3337E-08-.1056E-08
 .3985E-04-.1000E-03-.1722E-04-.3806E-10-.1056E-08 .2891E-08
EST. ST. ERRORS FOR EXPO. STA. IN METERS IN X 2.206       IN Y 2.291        IN Z 2.903
COVARIANCE MATRIX ON RANGE AND AZIMUTH

  RANGE      AZIMUTH
 .4845E+01-.5977E-05
-.5977E-05 .1283E-09

STANDARD ERROR IN RANGE .2201E+01METERS
STANDARD ERROR IN AZIMUTH .1133E-04RADIANS
```

```
PARAMETERS OF SAMPLE CASE
ALT 30000.000METERS
RANGE    202237.METERS
NUMBER OF CONTROL PTS.          5
WITH PHOTO COORDINATE STD ERRORS OF      .0100 MM IN X AND Y

COVARIANCE FOR EXTERIOR ORIENTATION

    XO          YO          ZO        KAPPA        PHI       OMEGA
.1413E+02-.5413E+01-.2429E+01 .6863E-05-.3077E-03 .1611E-03
.5413E+01 .1672E+02 .3087E+01 .2278E-05 .1129E-03-.3882E-03
.2429E+01 .3087E+01 .1154E+02-.6622E-05 .5543E-04-.8824E-04
.6863E-05 .2278E-05-.6622E-05 .1636E-08 .1554E-10-.7503E-10
.3077E-03 .1129E-03 .5543E-04 .1554E-10 .8537E-08-.3463E-08
.1611E-03-.3882E-03-.8824E-04-.7503E-10-.3463E-08 .1066E-07
EST. ST. ERRORS FOR EXPO. STA. IN METERS IN X 3.759       IN Y 4.089         IN Z 3.397
COVARIANCE MATRIX ON RANGE AND AZIMUTH

  RANGE      AZIMUTH
 .1336E+02-.2420E-04
-.2420E-04 .4089E-09


STANDARD ERROR IN RANGE .3655E+01METERS
STANDARD ERROR IN AZIMUTH .2022E-04RADIANS
```

```
PARAMETERS OF SAMPLE CASE
ALT 10000.000METERS
RANGE   400124.METERS
NUMBER OF CONTROL PTS.          5
WITH PHOTO COORDINATE STD ERRORS OF      .0020 MM IN X AND Y

COVARIANCE FOR EXTERIOR ORIENTATION

     XO         YO         ZO        KAPPA        PHI       OMEGA
.1792E+00-.3207E-01 .1579E-01-.8625E-06-.7777E-05 .1580E-05
.3207E-01 .2108E+00-.1817E-01 .5253E-07 .4140E-05-.5644E-05
.1579E-01-.1817E-01 .7335E+00-.1367E-05-.5343E-05 .3759E-05
.8625E-06 .5251E-07-.1367E-05 .9529E-10 .1109E-09-.1218E-10
.7777E-05 .4141E-05-.5343E-05 .1109E-09 .9974E-09-.2452E-09
.1580E-05-.5644E-05 .3759E-05-.1218E-10-.2452E-09 .5967E-09
EST. ST. ERRORS FOR EXPO. STA. IN METERS IN X  .423      IN Y  .459       IN Z  .856
COVARIANCE MATRIX ON RANGE AND AZIMUTH

  RANGE     AZIMUTH
 .1803E+00-.8127E-07
-.8127E-07 .1316E-11

STANDARD ERROR IN RANGE .4247E+00METERS
STANDARD ERROR IN AZIMUTH .1147E-05RADIANS
```

```
PARAMETERS OF SAMPLE CASE
ALT 10000.000METERS
RANGE   400124.METERS
NUMBER OF CONTROL PTS.          5
WITH PHOTO COORDINATE STD ERRORS OF     .0050 MM IN X AND Y

COVARIANCE FOR EXTERIOR ORIENTATION

     XO          YO          ZO        KAPPA        PHI        OMEGA
.5409E+00-.1482E+00-.3835E-01-.1902E-05-.3388E-04 .1328E-04
.1482E+00 .5833E+00 .8260E-01-.1018E-06 .1151E-04-.3333E-04
.3835E-01 .8260E-01 .9366E+00-.1505E-05 .2764E-05-.5741E-05
.1902E-05-.1018E-06-.1505E-05 .4889E-09 .2703E-09-.3805E-10
.3388E-04 .1151E-04 .2764E-05 .2703E-09 .3337E-08-.1056E-08
.1328E-04-.3333E-04-.5741E-05-.3806E-10-.1056E-08 .2891E-08
EST. ST. ERRORS FOR EXPO. STA. IN METERS IN X  .735      IN Y  .763       IN Z  .967
COVARIANCE MATRIX ON RANGE AND AZIMUTH

  RANGE      AZIMUTH
 .5393E+00-.3651E-06
-.3651E-06 .3643E-11

STANDARD ERROR IN RANGE .7343E+00METERS
STANDARD ERROR IN AZIMUTH .1908E-05RADIANS
```

```
PARAMETERS OF SAMPLE CASE
ALT 10000.000METERS
RANGE    400124.METERS
NUMBER OF CONTROL PTS.          5
WITH PHOTO COORDINATE STD ERRORS OF      .0100 MM IN X AND Y

COVARIANCE FOR EXTERIOR ORIENTATION

    XO          YO          ZO       KAPPA        PHI       OMEGA
.1570E+01-.6014E+00-.2699E+00 .2287E-05-.1025E-03 .5372E-04
.6014E+00 .1353E+01 .3430E+00 .7595E-06 .3765E-04-.1294E-03
.2699E+00 .3430E+00 .1282E+01-.2207E-05 .1847E-04-.2941E-04
.2287E-05 .7595E-06-.2207E-05 .1636E-08 .1554E-10-.7503E-10
.1025E-03 .3765E-04 .1847E-04 .1554E-10 .8537E-08-.3463E-08
.5372E-04-.1294E-03-.2941E-04-.7503E-10-.3463E-08 .1066E-07
EST. ST. ERRORS FOR EXPO. STA. IN METERS IN X 1.253      IN Y 1.363        IN Z 1.132
COVARIANCE MATRIX ON RANGE AND AZIMUTH

  RANGE      AZIMUTH
 .1556E+01-.1481E-05
-.1481E-05 .1160E-10


STANDARD ERROR IN RANGE .1247E+01METERS
STANDARD ERROR IN AZIMUTH .3406E-05RADIANS
```

```
PARAMETERS OF SAMPLE CASE
ALT 30000.000METERS
RANGE   401123.METERS
NUMBER OF CONTROL PTS.          5
WITH PHOTO COORDINATE STD ERRORS OF      .0020 MM IN X AND Y

COVARIANCE FOR EXTERIOR ORIENTATION

     XO          YO          ZO         KAPPA        PHI        OMEGA
.1613E+01-.2886E+00 .1421E+00-.2587E-05-.2333E-04 .4741E-05
.2886E+00 .1897E+01-.1635E+00 .1576E-06 .1242E-04-.1693E-04
.1421E+00-.1635E+00 .6602E+01-.4101E-05-.1602E-04 .1127E-04
.2587E-05 .1575E-06-.4101E-05 .9529E-10 .1109E-09-.1218E-10
.2333E-04 .1242E-04-.1603E-04 .1109E-09 .9974E-09-.2452E-09
.4741E-05-.1693E-04 .1127E-04-.1218E-10-.2452E-09 .5967E-09
EST. ST. ERRORS FOR EXPO. STA. IN METERS IN X 1.270       IN Y 1.377         IN Z 2.569
COVARIANCE MATRIX ON RANGE AND AZIMUTH

  RANGE      AZIMUTH
 .1662E+01-.7481E-06
-.7481E-06 .1179E-10

STANDARD ERROR IN RANGE .1289E+01METERS
STANDARD ERROR IN AZIMUTH .3434E-05RADIANS
```

```
PARAMETERS OF SAMPLE CASE
 ALT 30000.000METERS
 RANGE    401123.METERS
 NUMBER OF CONTROL PTS.          5
 WITH PHOTO COORDINATE STD ERRORS OF      .0050 MM IN X AND Y

COVARIANCE FOR EXTERIOR ORIENTATION

     XO         YO         ZO       KAPPA        PHI       OMEGA
 .4868E+01-.1333E+01-.3452E+00-.5706E-05-.1016E-03 .3985E-04
 .1333E+01 .5250E+01 .7434E+00-.3054E-06 .3455E-04-.1000E-03
 .3452E+00 .7434E+00 .8430E+01-.4515E-05 .8292E-05-.1722E-04
 .5706E-05-.3054E-06-.4515E-05 .4889E-09 .2703E-09-.3806E-10
 .1016E-03 .3455E-04 .8291E-05 .2703E-09 .3337E-08-.1056E-08
 .3985E-04-.1000E-03-.1722E-04-.3806E-10-.1056E-08 .2891E-08
 EST. ST. ERRORS FOR EXPO. STA. IN METERS IN X 2.206      IN Y 2.291         IN Z 2.903
COVARIANCE MATRIX ON RANGE AND AZIMUTH

  RANGE      AZIMUTH
 .4837E+01-.3177E-05
-.3177E-05 .3263E-10

STANDARD ERROR IN RANGE .2199E+01METERS
STANDARD ERROR IN AZIMUTH .5712E-05RADIANS
```

```
PARAMETERS OF SAMPLE CASE
 ALT 30000.000METERS
 RANGE   401123.METERS
 NUMBER OF CONTROL PTS.          5
 WITH PHOTO COORDINATE STD ERRORS OF      .0100 MM IN X AND Y

 COVARIANCE FOR EXTERIOR ORIENTATION

     XO          YO          ZO        KAPPA        PHI        OMEGA
 .1413E+02-.5413E+01-.2429E+01 .6863E-05-.3077E-03 .1611E-03
 .5413E+01 .1672E+02 .3087E+01 .2278E-05 .1129E-03-.3882E-03
 .2429E+01 .3087E+01 .1154E+02-.6622E-05 .5543E-04-.8824E-04
 .6863E-05 .2278E-05-.6622E-05 .1636E-08 .1554E-10-.7503E-10
 .3077E-03 .1129E-03 .5543E-04 .1554E-10 .8537E-08-.3463E-08
 .1611E-03-.3882E-03-.8824E-04-.7503E-10-.3463E-08 .1066E-07
 EST. ST. ERRORS FOR EXPO. STA. IN METERS IN X 3.759      IN Y 4.089       IN Z 3.397
 COVARIANCE MATRIX ON RANGE AND AZIMUTH

   RANGE      AZIMUTH
  .1375E+02-.1288E-04
 -.1288E-04 .1039E-09


  STANDARD ERROR IN RANGE .3709E+01METERS
  STANDARD ERROR IN AZIMUTH .1019E-04RADIANS
```

## SECTION III

## DISCUSSION OF RESULTS

The results tabulated in Section IIB. 3. 3. are measures of the combined influences of camera calibration and photo coordinate measurement errors. The geodetic bias errors are not considered. Recent estimates of the magnitude of the geodetic bias or fixed error[2] for the 200 and 400 km cases are approximately 0. 5 and 1. 0 meters, respectively. If these are combined quadratically with the control zone survey errors estimated at 0. 1 meter[2], the resulting geodetic fixed errors are (Estimated Standard Errors):

Range 200 km

| | | |
|---|---|---|
| Range Bias Error | ~ | $\pm$ 0. 5 meters |
| Azimuth Bias Error | ~ | $\pm 0.25 \times 10^{-5}$ radians (0. 5") |

Range 400 km

| | | |
|---|---|---|
| Range Bias Error | ~ | $\pm$ 1. 0 meters |
| Azimuth Bias Error | ~ | $\pm 0.25 \times 10^{-5}$ radians (0. 5") |

The consequence of the camera calibration errors alone without the effect of subsequent photo coordinate measurement errors is computed for influence on range and azimuth. This error is systematic in nature since the errors of calibration remain fixed. Their effect on range and altitude are (Estimated Standard Errors):

Altitude 10 km

Range Error ~ $\pm$ 0.3 meters

Azimuth Error:

at 200 km range ~ $\pm 0.15 \times 10^{-5}$ radians

at 400 km range ~ $\pm 0.75 \times 10^{-6}$ radians

Altitude 30 km

Range Error ~ $\pm$ 1.0 meters

Azimuth Error:

at 200 km ~ $\pm 0.5 \times 10^{-5}$ (1")

at 400 km ~ $\pm 0.25 \times 10^{-5}$ (0.5")

It is noted that the camera calibration errors contribute two thirds of the error due to the geodetic survey for altitudes of 10 km but are twice as large as the survey errors at 30 km altitudes for the 200 km range.

In the event that greater accuracy in range and azimuth is required than can be offered due to limitations caused by the fixed errors remaining in the camera calibration, a scheme of compensation may be employed. It is suggested that the principle of compensation be used that takes the mean value of results from pairs of flights in opposite directions. This procedure known in geodesy as observation in "direct and reverse" applies as well to the compensation of fixed camera errors. The details of this procedure remain to be worked out.

The results obtained above using photo coordinate standard errors of $\pm$ 10 microns are quite close to the earlier prediction[1] that the photogrammetric error (assuming 10 microns also) would be 1/10,000th of the flying height independently along each axis.

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## APPENDIX A

## DEVELOPMENT OF THE (F), (G) AND (H) MATRICES

The necessary partial derivatives for the elements of the (F) matrix are taken from equations (3a) and (3b)--(Section II. B. 2. ). For $\partial \bar{x}_i/\partial c$ and $\partial \bar{y}_i/\partial c$, equations (1a) and (1b) are used.

Let:

| | | |
|---|---|---|
| $R$ | = | $(x_i^2 + y_i^2)^{1/2}$ |
| $J$ | = | $(J1 \cdot R^2 + J2 \cdot R^4)$ |
| $K$ | = | $1 + K1 \cdot R^2 + K2 \cdot R^4 + K3 \cdot R^6$ |
| $\{x\}$ , $\{y\}$ | ~ | the $\{\}$ terms in equations (3a) &(3b), respectively |
| $\Delta X_i$ | = | $X_i - X_o$ |
| $\Delta Z_i$ | = | $Z_i - Z_o$ |
| $\Delta Y_i$ | = | $Y_i - Y_o$ |
| $\{\theta\}$ | ~ | the $\{\}$ term of equation (5) & $[\theta]$ ~ the $[\,]$ term of equation (5) |
| c | ~ | calibrated focal length |

$$f_{1,i} = \partial \bar{x}_i/\partial x_o = +1$$

$$f_{2,i} = \partial \bar{x}_i/\partial y_o = 0$$

$$f_{3,i} = \partial \bar{x}_i/\partial c = \Delta X_i/\Delta Z_i$$

$$f_{4,i} = \partial \bar{x}_i/\partial K1 = -\{x\} \cdot R^2/K^2$$

$$f_{5,i} = \partial \bar{x}_i/\partial K2 = -\{x\} \cdot R^4/K^2$$

$$f_{6,i} = \partial \bar{x}_i/\partial K3 = -\{x\} \cdot R^6/K^2$$

$$f_{7,i} = \partial \bar{x}_i / \partial J1 = + \frac{R^2 \sin \phi}{K}$$

$$f_{8,i} = \partial \bar{x}_i / \partial J2 = + \frac{R^4 \sin \phi}{K}$$

$$f_{9,i} = \partial \bar{x}_i / \partial \phi = J/K \cdot \cos \phi$$

$$f_{1,n+i} = \partial \bar{y}_i / \partial x_o = 0$$

$$f_{2,n+i} = \partial \bar{y}_i / \partial y_o = +1$$

$$f_{3,n+i} = \partial \bar{y}_i / \partial c = \Delta Y_i / \Delta Z_i$$

$$f_{4,n+i} = \partial \bar{y}_i / \partial K1 = + \{y\} \cdot R^2/K^2$$

$$f_{5,n+i} = \partial \bar{y}_i / \partial K2 = + \{y\} \cdot R^4/K^2$$

$$f_{6,n+i} = \partial \bar{y}_i / \partial K3 = + \{y\} \cdot R^6/K^2$$

$$f_{7,n+i} = \partial \bar{y}_i / \partial J1 = - R^2/K \cdot \cos \phi$$

$$f_{8,n+i} = \partial \bar{y}_i / \partial J2 = - R^4/K \cdot \cos \phi$$

$$f_{9,n+i} = \partial \bar{y}_i / \partial \phi = + J/K \cdot \sin \phi$$

The required derivatives for the (A) matrix appear in simplified form as the coefficients to the alterations to the estimates of exterior orientation in equations (lc) and (ld)--(Section B.1.).

$$A_{i,1} = \partial \bar{x}_i / \partial X_o = - \frac{c}{Z_i - Z_o}$$

$$A_{i,2} = \partial \bar{x}_i / \partial Y_o = 0$$

$$A_{i,3} = \partial \bar{x}_i / \partial Z_o = + \frac{c(X_i - X_o)}{(Z_i - Z_o)^2}$$

$$A_{i,4} = \partial \bar{x}_i / \partial k = c \frac{(Y_i - Y_o)}{(Z_i - Z_o)}$$

$$A_{i,5} = \partial \bar{x}_i / \partial \phi = c \, (1 + \frac{(X_i - X_o)^2}{(Z_i - Z_o)^2}$$

$$A_{i,6} = \partial \bar{x}_i / \partial \omega = + \frac{c(X_i - X_o)}{(Z_i - Z_o)^2} (Y_i - Y_o)$$

$$A_{n+i,1} = \partial \bar{y}_i / \partial X_o = 0$$

$$A_{n+i,2} = \partial \bar{y}_i / \partial Y_o = - \frac{c}{(Z_i - Z_o)}$$

$$A_{n+i,3} = \partial \bar{y}_i / \partial Z_o = c \frac{(Y_i - Y_o)}{(Z_i - Z_o)^2}$$

$$A_{n+i,4} = \partial \bar{y}_i / \partial k = -c \frac{(X_i - X_o)}{(Z_i - Z_o)}$$

$$A_{n+i,5} = \partial \bar{y}_i / \partial \phi = -c \frac{(Y_i - Y_o)}{(Z_i - Z_o)^2} (X_i - X_o)$$

$$A_{n+i,6} = \partial \bar{y}_i / \partial \omega = +c \, (1 + \frac{(Y_i - Y_o)^2}{(Z_i - Z_o)^2})$$

The necessary derivatives for the elements of (H) are taken from equations (4) and (5), Section II. B. 1.

$$h\,1.1 = \partial D/\partial X_o = + \frac{X_o - X_m}{D}$$

$$h\,2.1 = \partial D/\partial Y_o = \frac{Y_o - Y_m}{D}$$

$$h\,3.1 = \partial D/\partial Z_o = \frac{Z_o - Z_m}{D}$$

$$h_{1,2} = \partial \theta/\partial X_o = +0$$

$$h_{2,2} = \partial \theta/\partial Y_o = +1/D$$

$$h_{3,2} = \partial \theta/\partial Z_o = +0$$

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13. ABSTRACT

A photogrammetric resection technique is used as a basis for the initial calibration of a ground based radar (ASFIR). An analysis of the influences of errors in camera calibration and geodetic bias is developed. The errors in range and azimuth from the ground stations to the aircraft are computed using the results from a stellar calibration performed on the camera. The results confirm earlier predictions that the photogrammetric error contribution to error in range (standard error) amounts to about 1 part in 10,000 of the flying height along each coordinate axis. This error is to be augmented with the geodetic bias error estimated to be ± meter at 400 kilometers.

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| 14. KEY WORDS | LINK A | | LINK B | | LINK C | |
|---|---|---|---|---|---|---|
| | ROLE | WT | ROLE | WT | ROLE | WT |
| Interferometer<br>Photogrammetry<br>Photogrammetric Resection | | | | | | |

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