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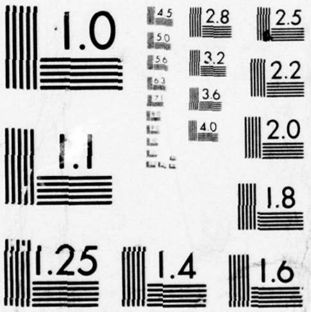

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DETERMINATION OF TRUE ELEVATIONS FROM AERIAL PHOTOGRAPHS

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MARCH 1977

FINAL REPORT

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DEAN OF THE FACULTY
UNITED STATES AIR FORCE ACADEMY
COLORADO 80840

Editorial Review by Lt Col Elser
Department of English and Fine Arts
USAF Academy, Colorado 80840

This research report is presented as a competent treatment of the subject, worthy of publication. The United States Air Force Academy vouches for the quality of the research, without necessarily endorsing the opinions and conclusions of the author.

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Philip J Erdle
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Vice Dean of the Faculty

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There are many problems involved in the determination of accurate elevations from tilted photographs. Plotting machines such as the Wild A-7 are able to compensate for tilt and provide accurate elevations, however, these machines are expensive and not available to many researchers. This report describes a set of procedures and a computer program for the determination of ground elevations to the same general degree of accuracy as that obtained with plotting machines. The procedures involve parallax measurements and location of points within a stereoscopic model.

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INTRODUCTION

Aerial photography is a tool frequently used in research. During such analysis, there are instances where the exact elevation of a point or several locations may be of value. This is commonly a requirement in the geomorphic interpretation of landforms, the investigation of geologic structure, and studies of geologic formations. In other cases, calculation of precise elevation values is required to construct contour maps.

Methods of elevation determination commonly used and presented in standard texts fall into two areas: relatively simple procedures based upon the radial displacement of a point from the photograph's principle point; and, use of stereoplotting machines. The first set of procedures has less than desired accuracy as it does not allow for the consequences of tilt in photographs.[1] The numerous plotting machines such as the Wild A-7 or Kelsh Plotter do make corrections for tilt in photographs and are very precise, however, these machines have the disadvantages of being quite expensive and very large. In addition, they are not available to most researchers.

This report deals with a series of procedures and a computer program which will allow the determination of elevation values from aerial photography to a similar degree of accuracy as plotting machines. This technique employs a parallax bar and grid to obtain

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[1] See T. Eugene Avery, Interpretation of Aerial Photographs, 3rd ed. (Minneapolis, Minnesota: Burgess Publishing Co., 1977), pp. 43-81; Paul R. Wolf, Elements of Photogrammetry (with Air Photo Interpretation and Remote Sensing), (New York: McGraw-Hill Inc., 1974), pp. 143-176.

the basic data regarding selected points within a stereoscopic model. The computer program converts these points to corrected elevations. The technique involved is well suited to the geographer, geologist, or other researcher who is, "prepared to take the trouble but whose work is insufficient or too sporatic to justify expenditure on more elaborate equipment."[2]

Development of the procedures and the associated computer program can be traced from A. R. Robbins' work in 1949, through E. H. Thompson's research in the 1950's, to B. D. P. Methley's contribution in 1970.[3] The techniques were first included in photogrammetry instruction at the University of Glasgow, with an updated approach offered in similar causes at the University of Georgia in 1972 by Dr. Roy Welch.[4] Terms colloquial to the procedure used and computer program are defined in Appendix A.

This report will discuss parallax, uses of the parallax bar, the effects of tilt in vertical photography, the computer program designed to eliminate these effects, and the applications of these procedures to contour mapping.

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[2] E.H. Thompson, "Heights from Parallax Measurements," Photogrammetric Record I (1954), p. 65.

[3] See A.R. Robbins, "Parallax," Photogrammetric Engineering XV (December 1949); Thompson, B.D.P. Methley, "Heights from Parallax Bar and Computer," Photogrammetric Record VI (1970).

[4] Roy Welch, "Parallax Bar and Computer Program," Lecture Notes, Athens, Georgia, 28 April 1972.

PARALLAX AND THE PARALLAX BAR

Any feature on the earth's surface which is photographed on successive vertical aerial photographs will naturally have a different location with relation to the center of each of the photographs. This difference in location or displacement is known as parallax and forms the basis for stereoscopic viewing of vertical photographs. The area of overlap, on successive photographs, normally sixty percent, forms a stereoscopic image or stereographic model when viewed under the proper conditions. Differences in parallax are directly related to differences in elevations.

The most accurate measurements of parallax are obtained through the use of a parallax bar and mirror stereoscope. Operation of a parallax bar requires the ability to interpret the "floating dot." Methely states that the, "Ultimate accuracy of results will depend upon the operators' ability to set the floating mark on the model."[5] Most image interpreters and others familiar with the use of aerial photographs can master the operation of the parallax bar in a relatively short time.

A parallax bar or stereometer (Figure 1) consists of two transparent plates with a small dot in their centers. The plates are located on a side of a metal bar. One of the plates is attached to the bar and records the distance between the two dots. When the dots are placed over the same image on successive photographs

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[5] Methley, 464.

and the stereographic model is viewed, the dots appear to unite and float. Changes in the distance between the dots cause the fused dot to appear to rise or fall in relation to the ground. When the fused dot appears to lie on the surface of the feature, the parallax between the points on the adjacent photographs can be read on the micrometer.[6] This value is used in the computer program to solve for the true elevation.

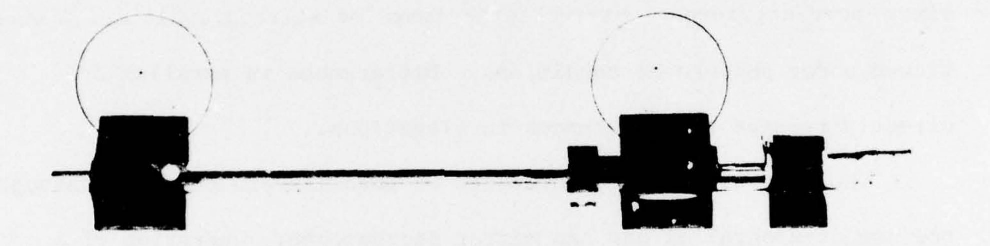

Figure 1. Parallax Bar

EFFECTS OF TILT

Because of the nature of the systems involved nearly all "vertical" aerial photographs contain some type of tilt and are not truly vertical. Tilt as described in this report is a rotation

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[6] See Avery, 57-58; Wolf, 148-151.

around an axis. Every aerial photograph has three axes around which tilt may be present (Figure 2).

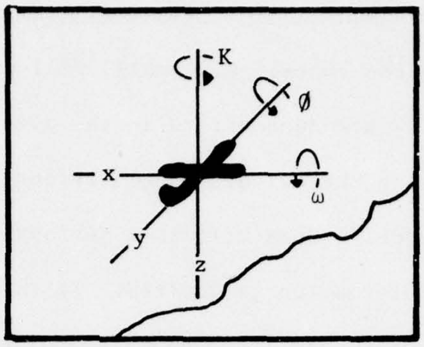

Figure 2. Axes of Tilt

Tilt around the Z axis is commonly called swing and is most commonly indicated as K (kappa) tilt. The Z axis extends through the aircraft in a vertical direction perpendicular to the line of flight. Dip is tilt around the Y axis and is termed Ø (phi) tilt. The Y axis is parallel to the line of flight. Tilt along the x axis is called ω (omega) tilt and is the result of wagging or roll. The combination of Ø and ω tilt causes a form of distortion in the photograph image called hyperbolic paraboloid deformation (Figure 3).[7]

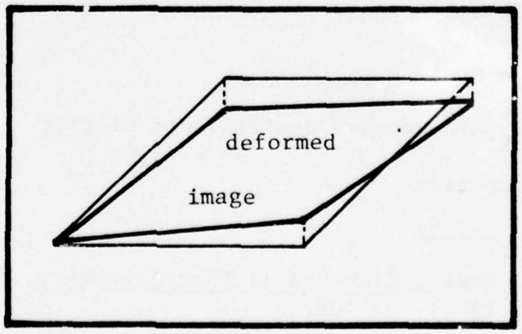

Figure 3. Hyperbolic Paraboloid Deformation

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[7] Welch, 1972.

It can be seen from this figure that tilt creates displacement of the object on the photograph from its orthographic or true location. Tilt also alters the scale throughout the image causing measurements to be inaccurate to a degree dependent upon the amount of tilt. "Tilt, unless exceedingly small, will cause displacements of images which will introduce errors in the parallax readings and consequently errors in the calculated elevations, sometimes of considerable magnitude."[8] Such tilt is a serious consideration when exact and precise information is desired. It is in the determination of the adjustments to be made to compensate for tilt that the computer program is used.

ELIMINATION OF THE EFFECTS OF TILT

The formula presented by Robbins in 1949 to determine true elevations did not deal with the effects of tilt.[9] Subsequently, Thompson attempted to eliminate such effects, and formulated the equation:

$$h'-h = a_o + a_1X + a_2Y + a_3XY + a_4X^2$$

where

h' = crude elevation

h = true elevation

a_1 thru a_4 are unknown coefficients of tilt

a_o is a constant

---

[8] Wilfred H. Baker, <u>Elements of Photogrammetry</u>, (New York: Ronald Press Co., 1960), p. 108.

[9] Robbins, 635.

a_1X and a_2Y correct for K tilt

a_3XY corrects for ω tilt

a_4X^2 eliminates the effects of ϕ tilt.

In describing the equation, Thompson pointed out that the formula can only be applied to the area within a stereoscopic model. To solve the equation at least five control points must be identified for which the true elevations are known.

Parallax Computer Program

Methley described a computer program used at the University of Glasgow which solved for the coordinates a_0 through a_4 in Thompson's equation. The program solves five simultaneous equations to obtain the unknown coefficients. These coefficients are then applied to other points within the stereoscopic model and the true elevations determined. Dr. Roy Welch at the University of Georgia has developed a modified version of this program using FORTRAN 4 language. The program yields results which approximate those derived from the use of more complex and expensive plotting machines. The program is shown in Appendix B.

The program requires the input of several types of data to solve the equations. Five control points must be identified within the stereoscopic model for which the true elevations are known. The photograph base length in centimeters and height of the camera above the terrain in feet are also required. In addition, the location of all control points and unknown points for which the elevation is desired must be identified in terms of x and y coordinates. Coordinates used in the program are expressed in millimeters with the origin of the grid on the photograph base line midway between the principle point and conjugate principle points. Parallax measurements for all control and unknown points are also required. Methley reported that the amount of error resulting from use of the parallax bar and computer program was on the order of 0.25 percent of the aircraft flying height.[10]

APPLICATIONS

The procedures and computer program described in this report have many military and civilian applications. It would be quite easy to accurately determine the height of a series of bridges over water bodies using this methodology. Areas of suspected land subsidences could also be identified from vertical photographs and the amount of subsidence established. Analysis of changes in landform configuration through time could be enhanced by use of these procedures, utilizing photography from different dates.

Probably the most apparent application of accurate elevations is in contour mapping. In many cases, researchers have a need for a contour map of an area where none is available. Such a map could be constructed through use of this program and procedures once stereoscopic imagery of the area is obtained. After the corrected

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[10] Methley, 459.

elevations are determined they are plotted in their relative location on tracing paper and placed over one of the photographs within the stereoscopic model. Contour lines may then be drawn on the tracing paper while viewing the model. Elevations and contour lines being drawn appear to be marked on the ground within the stereoscopic model.

In conjunction with this report, research was conducted to determine whether a contour map constructed from a number of points arranged in a uniform pattern (Figure 4) could approximate the accuracy of a contour map compiled from points specifically selected for their location, i.e., hilltops, stream beds. The two sets of parallax measurements were taken through the use of a mirror stereoscope and parallax bar. The computer program using the parallax and other necessary data was run to determine the true elevations of all points. Two contour maps were then constructed using the true elevations.

Analysis of the maps showed that the map constructed from forty specifically selected points contained a greater amount of error than the map prepared from thirty-eight points taken from the uniform grid.

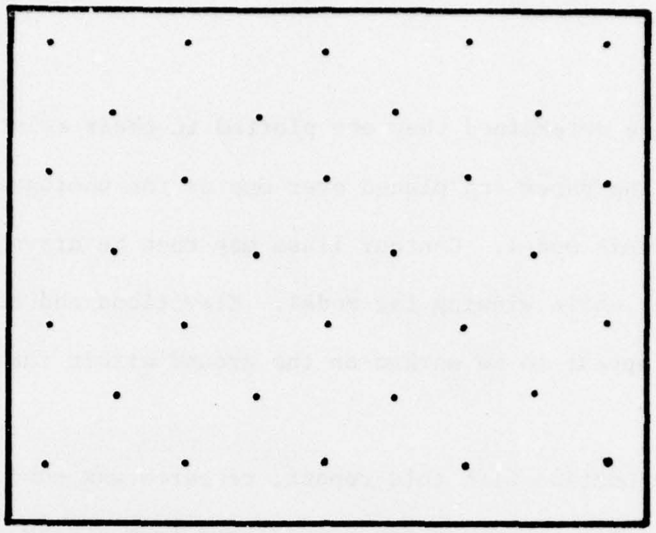
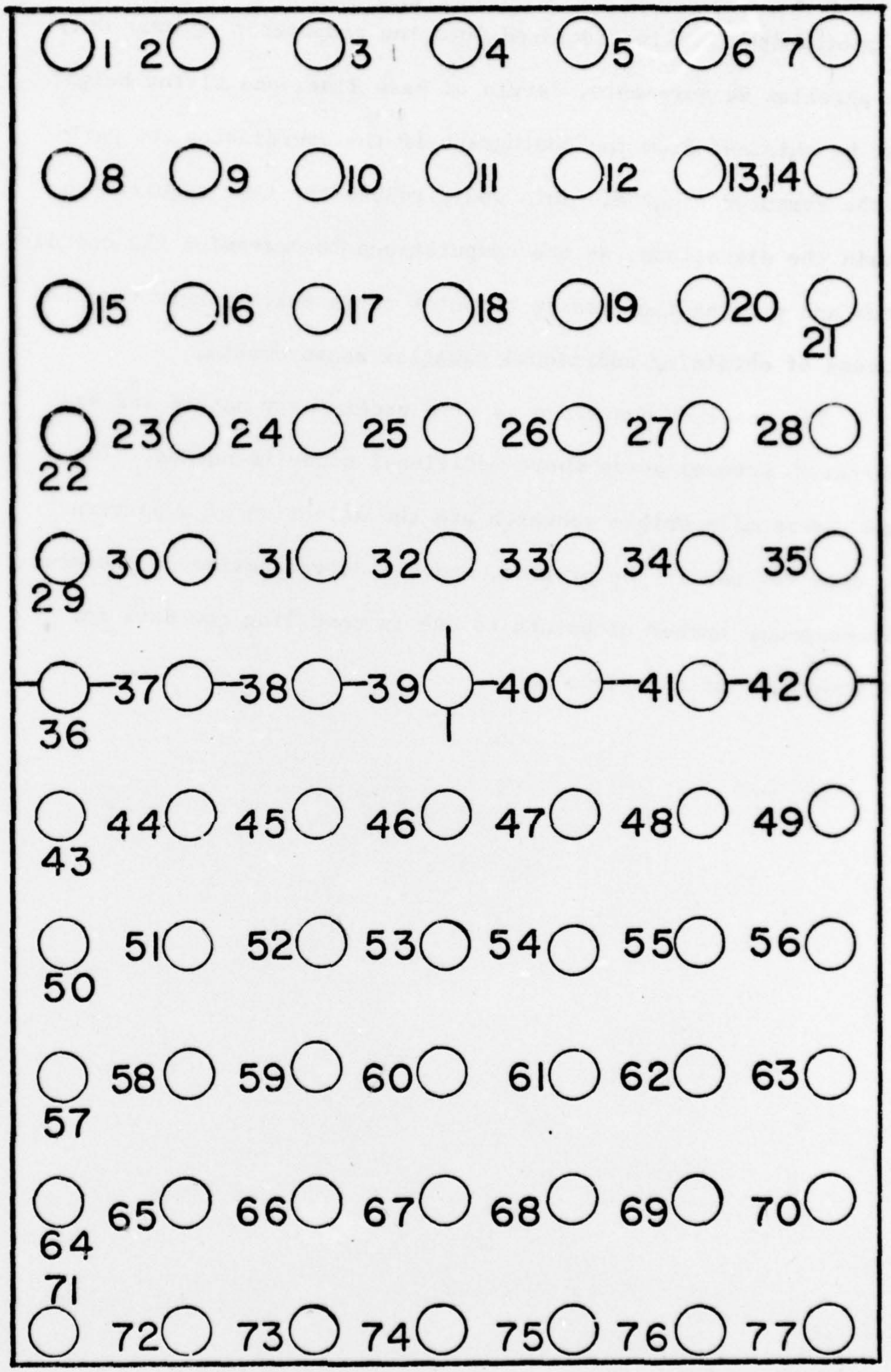


Figure 4. Dot Pattern

SUMMARY

Based upon this initial investigation, it is concluded that a set of points arranged in a pattern does provide greater accuracy than points critically selected for their usefulness. The use of a pattern in the selection of points can be easily incorporated into the existing procedures. A plastic sheet resembling that shown in Figure 5 could be produced for the standard 9 by 9 inch vertical photographs and the 5.4 by 9 stereoscopic model formed by their overlap. Such a grid would require no scale and could, therefore, be used on any vertical stereoscopic model. The grid would have the photographic base line indicated and the origin of the coordinate system marked. A grid of this nature would allow the x and y coordinates of each point to be determined without reference



GRID FOR PARALLAX MEASURMENTS

Figure 5

to photography and incorporated into the computer program. Only the parallax measurements, length of base line, and flying height must be obtained from the photograph if the coordinates are part of the computer program. This would reduce the time required to obtain the elevations, as the computations to determine the coordinates and placing the data on computer cards takes longer than the process of obtaining additional parallax measurements.

The research described is of a preliminary nature and has indicated several areas where additional study is needed. Two such areas of possible research are the selection of a pattern of dots for use in the program, and the determination of the most advantageous number of points to use in compiling the data for construction of a contour map.

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APPENDIX A

Conjugate principle point: The location of the principle point of a photograph on the adjacent photograph.

Parallax: *Parallax is the displacement in position of an object on* two photographs which results from the change in position of the camera taking the photographs.

Photo Base Length: The distance between a photographs principle point and the principle point on an adjacent print.

Stereomodel: That portion of adjacent photographs where the image may be viewed in three dimensions.

Tilt: The angle or amount of rotation around any axis of a photograph.

APPENDIX B

```
C     PARALLAX PROGRAM

      DIMENSION HA(50),X(50),Y(50),XP(50),PA(50),A(5,5),HT(5)
      DIMENSION C(5),DP(50),DH(50),H(50)
      READ(5,200)N,HL,B,(HA(I),I=1,5)

  200 FORMAT(6X,I2,2F10.2/6X,5F10.2)
      WRITE(6,205)N,HL,B,(HA(I),I=1,5)

  205 FORMAT(1H1,11HNO. OF DATA,10X,13HCAMERA HEIGHT,10X,
     111HBASE LENGTH,19X,14HGROUND CONTROL/4X,I2,16X,F10.2,
     210X,F10.2,5X,5F10.2)
      READ(5,210) (XP(I),X(I),Y(I),I=1,N)
  210 FORMAT(6X,3F10.2)
      WRITE(6,213)
  213 FORMAT(1H0,19X,2HXP,9X,1HX,9X,1HY)
      WRITE(6,215) (XP(I),X(I),Y(I),I=1,N)
  215 FORMAT(1H ,13X,3F10.2)
      WRITE(6,107)
  107 FORMAT(1H1,11HDATA NUMBER, 10X,21HDIFFERENTIAL PARALLAX)
      I=1
      M=1

    1 I=I+1
    2 IF(I-N) 5,5,9
    5 DP(I)=XP(I)-XP(M)
    6 WRITE(6,7) I,DP(I)
    7 FORMAT(1H ,5X,I2,20X,F6.3)
    8 GO TO 1
    9 CONTINUE
      WRITE(6,115)
  115 FORMAT(1H1,11HDATA NUMBER,10X,17HPARALLAX,ABSOLUTE)
   10 I=1
   12 I=I+1
   13 IF(I-N) 14,14,17
   14 PA(I)=DP(I)+B
  141 WRITE(6,15) I, PA(I)
   15 FORMAT(1H ,5X,I2,20X,F5.2)
   16 GO TO 12
   17 CONTINUE
      WRITE(6,127)
  127 FORMAT(1H1,11HDATA NUMBER,10X,24HDELTA HEIGHT ABOVE DATUM)
   18 I=1
   19 I=I+1
   20 IF(I-N) 22,22,29
```

```
22  DH(I)=(HL*HF(I))/HA(I)
26  WRITE(6,27) I, DH(I)
27  FORMAT(1H ,5X,I2,20X,F8.2)
28  GO TO 19
29  CONTINUE
    WRITE(6,137)
137 FORMAT(1H1,11HDATA NUMBER,13X,15HCRUDE ELEVATION)
30  I=1
31  M=1
32  I=I+1
33  IF(I-N) 34,34,39
34  H(I)=DH(I)+HA(M)
36  WRITE(6,37) I,H(I)
37  FORMAT(1H ,5X,I2,20X,F8.2)
38  GO TO 32
39  CONTINUE
40  HT(1)=0
41  HT(2)=HA(2)-H(2)
42  HT(3)=HA(3)-H(3)
43  HT(4)=HA(4)-H(4)
44  HT(5)=HA(5)-H(5)
45  DO 51 I=1,5
46  A(I,1)=1
47  A(I,2)=X(I)
48  A(I,3)=Y(I)
49  A(I,4)=X(I)*Y(I)
50  A(I,5)=X(I)**2
51  CONTINUE
52  CALL INVNN (A,5,5)
53  CALL VMATMF (A,HT,C,5,5,1)
54  WRITE(6,55) C
55  FORMAT(1H0,5F10.3,5X,40HARE COEFFICIENTS FOR C12345 RESPECTIVELY)
    WRITE(6,170)
170 FORMAT(1H0,11HDATA NUMBER,10X,19HCORRECTED ELEVATION)
65  I=5
66  I=I+1
67  IF(I-N) 68,68,75
68  HA(I)=C(1)+(C(2)*X(I))+(C(3)*Y(I))+(C(4)*X(I)*Y(I))+(C(5)*X(I)**2)
    HA(I)=HA(I)+H(I)
    K=I-5
69  WRITE(6,70) K,HA(I)
70  FORMAT(1H ,5X,I2,19X,F8.2)
71  GO TO 66
75  CONTINUE
76  STOP
    END
```

```
      SUBROUTINE INVMD(B,N,M)
      DIMENSION B(1),G(70)
      IDUM1=0
      K1=0
      DO 300 K=1,N
      DO 350 I=1,N
  350 G(I)=0.
      K1=K1+1
      G(K)=1./B(K1)
      KJ=K
      DO 400 J=2,N
      KJ=KJ+M
  400 B(KJ)=B(KJ)/B(K1)
      I1=0
      DO 550 I=1,N
      I1=I1+1
      IF(I-K) 450,550,450
  450 G(I)=G(I)-B(I1)*G(K)
      IJ=I
      KKJ=K
      DO 500 J=2,N
      IJ=IJ+M
      KKJ=KKJ+M
  500 B(IJ)=B(IJ)-B(I1)*B(KKJ)
  550 CONTINUE
      IN=(N-1)*M
      DO 650 I=1,N
      IJ1=I-M
      IJ=I
      DO 600 J=2,N
      IJ=IJ+M
      IJ1=IJ1+M
  600 B(IJ1)=B(IJ)
      IN=IN+1
  650 B(IN)=G(I)
  300 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE VMATMP(A.B.C,I,J,K)
C     DIMENSION A%I,J<.B%J.K<,C%I,K<
      DIMENSION A(1),B(1).C(1)
      DO 2 L=1,I
      KK=L-I
      III=KK
      JJ=0
      DO 2 M=1,K
      CD=0.
      II=III
      DO 1 N=1,J
      II=II+I
      JJ=JJ+1
    1 CD=CD+A(II)*B(JJ)
      KK=KK+I
    2 C(KK)=CD
      RETURN
      END
```

```
     CAMERA HEIGHT           BASE LENGTH                        GROUND CONTROL
        5700.00                 88.00           600.00    642.00     540.00     520.00     668.00
   X2            X            Y
  11.24         1.84         1.00
  12.00        -2.96         9.30
  10.25        -2.36        -7.40
   7.43         3.63        -9.20
  11.03         4.04         8.00
  11.56        -2.36         6.50
  11.52         6.56         5.25
   9.79        -1.26        -5.01
  10.72         0.04        -2.30
  10.28         6.84         4.75
  11.58         6.14         1.60
   8.51         6.24        -4.20
  12.46         1.44        10.60
  11.40        -1.56        10.00
  11.59        -4.76         2.60
  11.80        -2.96         2.40
  11.71        -0.26         2.10
   9.67        -1.61        -2.40
   8.60        -3.23        10.90
   7.95         0.24       -10.00
   8.16         3.74        -3.30
   9.20         2.04        -1.50
  10.00        -6.46        -4.90
   8.80         1.66        -7.30
  10.30        -3.66        -6.10
  11.19        -0.16        -0.90
  10.38        -0.06        -4.40
  11.70         0.84         7.30
  10.84         3.94         9.55
  12.07        -0.16         6.20
   5.27        -1.56        -8.40
   9.85         5.94         0.30
   7.40         5.74        -7.40
  11.43         0.74         1.00
```

```
DATA NUMBER          DIFFERENTIAL PARALLAX
     2                      0.720
     3                     -1.030
     4                     -3.800
     5                     -0.250
     6                      0.260
     7                      0.240
     8                     -1.400
     9                     -0.590
    10                     -1.390
    11                      0.300
    12                     -2.770
    13                      1.180
    14                      0.120
    15                      0.310
    16                      0.520
    17                      0.430
    18                     -1.610
    19                     -2.680
    20                     -3.330
    21                     -3.120
    22                     -2.060
    23                     -1.280
    24                     -2.450
    25                     -0.980
    26                     -0.090
    27                     -0.900
    28                      0.420
    29                     -0.440
    30                      0.790
    31                     -3.010
    32                     -1.430
    33                     -3.380
    34                      0.150
```

```
DATA NUMBER          PARALLAX,ABSOLUTE
     2                     85.72
     3                     86.07
     4                     84.20
     5                     87.75
     6                     85.28
     7                     85.24
     8                     85.51
     9                     87.44
    10                     87.00
    11                     85.30
    12                     85.23
    13                     85.18
    14                     85.12
    15                     85.31
    16                     85.52
    17                     85.43
    18                     86.39
    19                     85.32
    20                     84.67
    21                     84.88
    22                     85.92
    23                     86.72
    24                     85.52
    25                     87.02
    26                     87.01
    27                     87.10
    28                     85.42
    29                     87.56
    30                     85.79
    31                     84.99
    32                     86.57
    33                     86.12
    34                     85.15
```

```
DATA NUMBER          DELTA HEIGHT ABOVE DATUM
     2                        46.46
     3                       -67.77
     4                      -258.24
     5                       -16.30
     6                        18.15
     7                        15.56
     8                       -98.55
     9                       -36.65
    10                       -65.77
    11                        19.44
    12                      -185.97
    13                        25.71
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    27                       -59.13
    28                        27.18
    29                       -28.75
    30                        50.91
    31                      -202.65
    32                       -34.52
    33                      -263.92
    34                         9.74
```

```
DATA NUMBER                          CRUST ELEVATION
      2                                  646.44
      3                                  532.23
      4                                  341.76
      5                                  583.70
      6                                  618.15
      7                                  615.58
      8                                  501.48
      9                                  563.35
     10                                  534.23
     11                                  619.44
     12                                  414.03
     13                                  675.71
     14                                  607.79
     15                                  620.09
     16                                  633.61
     17                                  627.42
     18                                  493.36
     19                                  420.27
     20                                  274.06
     21                                  389.67
     22                                  461.48
     23                                  515.54
     24                                  434.07
     25                                  535.56
     26                                  594.14
     27                                  540.87
     28                                  627.18
     29                                  571.25
     30                                  650.91
     31                                  397.35
     32                                  505.48
     33                                  336.08
     34                                  600.74
   -46.798          9.363          -4.174          -0.671          10.311
DATA NUMBER                       CORRECTED ELEVATION
      1                                  589.02
      2                                 1028.95
      3                                  475.07
      4                                  526.68
      5                                  992.32
      6                                 1005.65
      7                                  862.35
      8                                  609.36
      9                                  540.28
     10                                  759.97
     11                                  684.25
     12                                  570.06
     13                                  465.71
     14                                  490.01
     15                                  374.42
     16                                  544.25
     17                                  485.08
     18                                  837.83
     19                                  426.04
     20                                  603.16
     21                                  549.84
     22                                  511.61
     23                                  561.01
     24                                  656.25
     25                                  577.54
     26                                  387.37
     27                                  875.74
     28                                  750.25
     29                                  570.91
```