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MEASUREMENTS OF RANGE, DEFLECTION,  
AND HEIGHT OF BURST FOR  
FIRED ARTILLERY SHELL, METHOD II -  
A LEAST-SQUARES METHODOLOGY

NEAL P. ROBERTS

FEBRUARY 1991

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My efforts in writing this report are dedicated to my mother, my Uncle Tony (her brother), my Aunt Etta (her sister), and all the other good people of the state of Connecticut, U.S.A. They are my strength and inspiration.

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## 1. INTRODUCTION

The purpose of this report is to explain a new mathematical method of measuring the range, deflection, and height of burst for a fired artillery shell. This new mathematical procedure can be used as an alternative to triangulation (Roberts 1990). It can be employed when there are three or more tower readings of azimuth and elevation on a fired projectile.

In triangulation, when three or four tower readings of azimuth and elevation are observed and the smallest optimum triangle whose area is less than 50 square meters is found, range, deflection, and height of burst are computed as follows. Range is the distance from the gun to center of "impact point" in the found triangle. Deflection from line of fire is computed as a perpendicular distance from "impact" to the line of fire and as an angle between line of fire and vector from weapon to "impact point." Altitudes are computed from each tower using the associated elevation and tower height and are then averaged (Roberts 1990).

The new technique operates differently. A least-squares method which minimizes angular error is employed iteratively to find the range, deflection, and height of burst point while making use of the same data input to triangulation. The procedure is used for all tower readings as well as for all combinations when one tower reading is omitted. Then, statistically, error computations and associated burst points can be compared to see if there is significant difference. Thus, this method provides a means of detecting a bad tower azimuth/elevation observation in the process of using all the information one has access to.

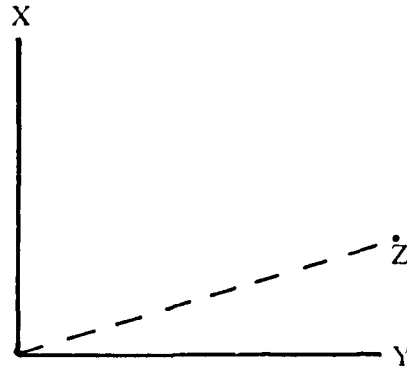
This report will first present the algorithms used in this technique. Then, a discussion of the algorithms and associated computer programs (Appendices A, B, C, and D) will follow. The conclusion will discuss the results of computer runs by both triangulation and the new technique applied to the same observational data input.

## 2. ALGORITHMS

2.1 Least-Squares<sup>†</sup>Algorithm (developed by Mr. Robert Lieske and used in subroutine LSTQR in least-squares computer program).

<sup>†</sup> For more information on least-squares, see "Introduction to Statistical Theory," by P. G. Hoel, S. C. Port, and C. T. Stone, 1971.





$(X_i, Y_i, Z_i)$  - position coordinates of burst point formed by two intersecting tower azimuth readings and an elevation from one tower.

Step 1. For burst point position  $(X_i, Y_i, Z_i)$ , compute root mean square errors in azimuth (ERMS) and elevation (ERMSEL) from  $n$  tower reading locations.

Let,

$\Delta AZ_k$  = azimuth angle (of segment from tower  $k$  to burst point) -  $AZ(I,K)$  (azimuth reading of round from tower  $k$ ), and

$\Delta EL_k$  = elevation angle (of segment from tower  $k$  to burst point) -  $ALZ(I,K)$  (elevation reading of round from tower  $k$ ).

Then,

$$ERMS = \left[ \sum_{k=1}^N \frac{(\Delta AZ_k)^2}{n} \right]^{1/2} ; \quad ERMSEL = \left[ \sum_{k=1}^N \frac{(\Delta EL_k)^2}{n} \right]^{1/2} \quad (1)$$

Step 2. Find  $\Delta X, \Delta Y, \Delta Z$  so that the following quantities are minimized where from a tower position  $(X(k), Y(k), Z(k))$ , one has for  $k = 1, \dots, n$ :

$$X_k = X_i - X(k);$$

$$Y_k = Y_i - Y(k);$$

$$Z_k = Z_i - Z(k);$$

$$E^2 = \sum_{k=1}^N \left[ \Delta AZ_k - \frac{\partial \Delta AZ_k}{\partial \Delta X} \Delta X - \frac{\partial \Delta AZ_k}{\partial \Delta Y} \Delta Y - \frac{\partial \Delta AZ_k}{\partial \Delta Z} \Delta Z \right]^2 \quad (2)$$

$$E^2 = \sum_{k=1}^N \left[ \Delta EL_k - \frac{\partial EL_k}{\partial \Delta X} \Delta X - \frac{\partial EL_k}{\partial \Delta Y} \Delta Y - \frac{\partial EL_k}{\partial \Delta Z} \Delta Z \right]^2 \quad (3)$$

Take the partial derivative of  $E^2$  in Equation 2 with respect to  $\Delta X$  and  $\Delta Y$  and take the partial derivative of  $E^2$  in Equation 3 with respect to  $\Delta Z$ . Set each partial derivative to zero and rearrange terms to give the following equations:

$$\sum \Delta AZ_k \left( \frac{\partial AZ_k}{\partial \Delta X} \right) = \sum \left( \frac{\partial AZ_k}{\partial \Delta X} \right)^2 \Delta X + \sum \left( \frac{\partial AZ_k}{\partial \Delta Y} \right) \left( \frac{\partial AZ_k}{\partial \Delta X} \right) \Delta Y + \sum \left( \frac{\partial AZ_k}{\partial \Delta Z} \right) \left( \frac{\partial AZ_k}{\partial \Delta X} \right) \Delta Z ; \quad (4)$$

$$\sum \Delta AZ_k \left( \frac{\partial AZ_k}{\partial \Delta Y} \right) = \sum \left( \frac{\partial AZ_k}{\partial \Delta X} \right) \left( \frac{\partial AZ_k}{\partial \Delta Y} \right) \Delta X + \sum \left( \frac{\partial AZ_k}{\partial \Delta Y} \right)^2 \Delta Y + \sum \left( \frac{\partial AZ_k}{\partial \Delta Z} \right) \left( \frac{\partial AZ_k}{\partial \Delta Y} \right) \Delta Z ; \quad (5)$$

$$\sum \Delta EL_k \left( \frac{\partial EL_k}{\partial \Delta Z} \right) = \sum \left( \frac{\partial EL_k}{\partial \Delta X} \right) \left( \frac{\partial EL_k}{\partial \Delta Z} \right) \Delta X + \sum \left( \frac{\partial EL_k}{\partial \Delta Y} \right) \left( \frac{\partial EL_k}{\partial \Delta Z} \right) \Delta Y + \sum \left( \frac{\partial EL_k}{\partial \Delta Z} \right)^2 \Delta Z . \quad (6)$$

Note the following terms can be derived:

$$\frac{\partial AZ_k}{\partial \Delta X} = - \frac{Y_k}{X_k^2 + Y_k^2} , \quad \frac{\partial AZ_k}{\partial \Delta Y} = \frac{X_k}{X_k^2 + Y_k^2} , \quad \frac{\partial AZ_k}{\partial \Delta Z} = 0 \quad (k=1, \dots, n) ;$$

$$\frac{\partial EL_k}{\partial \Delta X} = \frac{-X_k Z_k}{(X_k^2 + Y_k^2 + Z_k^2)(X_k^2 + Y_k^2)^{1/2}} \quad (k=1, \dots, n) ;$$

$$\frac{\partial EL_k}{\partial \Delta Y} = \frac{-Y_k Z_k}{(X_k^2 + Y_k^2 + Z_k^2)(X_k^2 + Y_k^2)^{1/2}} \quad (k=1, \dots, n) ;$$

$$\frac{\partial EL_k}{\partial \Delta Z} = \frac{-(X_k^2 + Y_k^2)^{1/2}}{(X_k^2 + Y_k^2 + Z_k^2)} \quad (k=1, \dots, n) .$$

With the above terms substituted into Equations 4, 5, 6, one notices that Equations 4 and 5 become two equations in the two unknowns  $\Delta X$ ,  $\Delta Y$ , and Equation 6 is one equation in the unknowns  $\Delta X$ ,  $\Delta Y$ ,  $\Delta Z$ .

Solve Equations 4 and 5 simultaneously to obtain  $\Delta X$ ,  $\Delta Y$ . Substitute the values  $\Delta X$ ,  $\Delta Y$  just obtained into Equation 6 so the  $\Delta Z$  can be solved for. One has just computed  $\Delta X$ ,  $\Delta Y$ ,  $\Delta Z$  so that Equations 2 and 3 have been minimized.

Step 3. If  $\Delta X$ ,  $\Delta Y$ ,  $\Delta Z < .1$ , then the point taken as the burst point is  $(X_i, Y_i, Z_i)$ . Otherwise, compute new  $X_i$ ,  $Y_i$ ,  $Z_i$  values as follows:

$$X_i = X_i - \Delta X;$$

$$Y_i = Y_i - \Delta Y;$$

$$Z_i = Z_i + \Delta Z;$$

and then repeat steps 1, 2, and 3. If the process does not converge in 200 iterations, a message, "DOES NOT CONVERGE," is printed out.

This algorithm can be applied to the case of all towers and to the case where each combination of one tower is omitted.

2.2 Modified F-Test Algorithm<sup>†</sup> With Outlier Scheme - (used in subroutines MODF and OUTLY in least-squares computer program).

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<sup>†</sup> For more information on the modified F-Test algorithm, see "Introduction to Statistical Analysis," by W. J. Dixon and F. J. Massey, 1957.

Using algorithm 2.1), one obtains the following values:

- ERROR (J) - Erms (azimuth)
- ERRORE(J) - Erms (elevation - el)
- XCNT (J) - X coordinate of burst point
- YCNT (J) - Y coordinate of burst point
- ZCNT (J) - Z coordinate of burst point

when omitting tower J (J = 1,...,n) and when all towers are used the following:

- ERROR (JALL) - Erms (azimuth)
- ERRORE(JALL) - Erms (elevation - el)
- XCNT (JALL) - X coordinate of burst point
- YCNT (JALL) - Y coordinate of burst point
- ZCNT (JALL) - Z coordinate of burst point

Step 1. Find smallest ERROR(J) that is less than ERROR(JALL). If any, conduct modified F-test with outlier scheme as follows:

$$\bar{x} = \sum_{K=1}^{n+1} \frac{ERROR(K)}{n+1} ;$$

$$\bar{x}' = \sum_{\substack{K=1 \\ K \neq J}}^{n+1} \frac{ERROR(K)}{n} ;$$

$$S = \sum_{K=1}^{n+1} (ERROR(K) - \bar{x})^2 ;$$

$$S' = \sum_{\substack{K=1 \\ K \neq J}}^{n+1} (ERROR(K) - \bar{x}')^2 ;$$

$$F_{n+1} = \frac{S'}{S} .$$

Step 2. Check to see if  $F_{n+1}$  derived from modified F-test is significant (i.e., is an outlier) using  $n+1$  degrees of freedom. Subroutine OUTLY in least-squares computer program has data statements giving criterion for 10%, 5%, 2.5% and 1% levels of significance and up to 8 degrees of freedom (Spiegel 1975; Hoel, Port, and Stone 1971).

If ERROR(J) is found to be significantly smaller than ERROR(JALL), then along with range, deflection, burst height (HOB), and error values of burst point found using all towers, similar values for burst position found with tower J omitted are also printed out.

Step 3. Find smallest ERRORE(J) that is less than ERRORE(JALL). If any, conduct modified F-test with outlier scheme in a manner similar to Steps 1 and 2.

### 3. DISCUSSION

After running the least-squares computer program (Appendix B) modified with special write statements on the sample observational data input of Appendix C, the process of convergence of the least-squares algorithm was investigated. It was found that when using all towers or when a tower was omitted, convergence took place in three or less iterations of the subroutine LSTQR. Also, the root mean square errors had the tendency to reduce in the iteration process. This, of course, is expected. When the convergence process was begun at a different initial burst point  $(X_i, Y_i, Z_i)$  by changing the combination of intersecting tower reading azimuths and tower elevation, it ended at the same point. That is, although the initial  $(X_i, Y_i, Z_i)$  of the convergent process was changed, the final  $(X_i, Y_i, Z_i)$  was invariant and produced the same identical output in Appendix D.

It must be admitted that the convergent process of the least-squares algorithm was not studied in great detail. A statement of theorem dealing with convergence or divergence of the algorithm was unable to be made and proven by the author. Perhaps some pure mathematician who reads this report will make such an attempt.

### 4. CONCLUSION

The least-squares computer program which utilizes the least-squares algorithm is contained in Appendix B with associated information in Appendix A. This computer program along with Dennis Flaherty's triangulation computer program has been applied to the same observational data input (Appendix C), and the results are shown in Appendices D and E. Appendices D and E show that the

least-squares computer program either with all towers or with a tower omitted give results in deflection, range, and height of burst that are similar to the results of the triangulation program for rounds 11 through 17. Round 18, however, is an interesting case. Depending on the computer program, the range values for this round differ absolutely by some 20 meters. Which program does one believe in? The author believes the results of the least-squares computer program because it uses all the information and there is no statistical reason for eliminating any of the four tower azimuth readings.

Note that the least-squares computer program can incorporate time of flight observational measurements in the same manner as the triangulation program (Roberts 1990). Also, the least-squares computer program has been written for the Aberdeen Proving Ground (APG) where azimuths are measured clockwise from due south, and the Cartesian coordinate system at the gun has its x-axis oriented 35° clockwise from due south, with positive z-axis going into the ground. This program can easily be adapted to the coordinate systems of other proving grounds. The least-squares computer program is on the VAX 8600 and VAX 780 computers in the Launch and Flight Division of the U.S. Army Ballistic Research Laboratory, APG, MD.

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## 5. REFERENCES

Dixon, W. J., and F. J. Massey. Introduction to Statistical Analysis. New York: McGraw-Hill Book Company, Inc., New York, 1957.

Hoel, P. G., S. C. Port, and C. T. Stone. Introduction to Statistical Theory. New York: Houghton Mifflin Company, 1971.

Roberts, N. P. "Measurements of Range, Deflection, Time of Flight, and Height of Burst for Field Artillery Shell Method I Triangulation." BRL-MR-3854, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, September 1990.

Spiegel, M. Probability and Statistics. New York: McGraw-Hill Book Company, Inc., 1975.



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**APPENDIX A:  
LISTING OF INPUT TO LEAST-SQUARES COMPUTER PROGRAM;  
DEFINITIONS OF INPUT TO LEAST-SQUARES COMPUTER PROGRAM;  
DESCRIPTION OF OUTPUT TO LEAST-SQUARES COMPUTER PROGRAM;**

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DEFINITIONS OF INPUT TO LEAST-SQUARES COMPUTER PROGRAM

XT, YT, ZT	Position coordinates of T-th tower (T .LE. 6) in APG grid system
ITOWER	Tower number (1,2,3,4,5,6)
IP	Any character other than a blank
X(7), Y(7), Z(7)	Position coordinates of weapon, APG system
AZDG, AZMG	Line of fire measured clockwise from south, in degrees and minutes
AZD, AZM	Tower azimuth readings measured from south, in degrees and minutes
EZD, EZM	Tower elevation readings of burst height, in degrees and minutes
ID1, ID2	Round identification

LISTING OF INPUT TO LEAST-SQUARES COMPUTER PROGRAM

All input is punched into a file using the following format.

Items	Format
XT, YT, ZT, ITOWER, IP	3F10.2, 47X, I1, 1X, A1
.	
XN, YN, ZN, ITOWER, IP    N .LE. 6	
Blank	
X(7), Y(7), Z(7), AZDG, AZMG	3F10.2, 2F10.1
For N of Towers:	
AZD(I, J), AZM, EZD, EZM, ID1, ID2	2F7.2, 2F7.2, 2X, 2A3
If blank data use -999. for both AZD and EZD	
.	
AZD(K, J)	
+999.	

DESCRIPTION OF OUTPUT TO LEAST-SQUARES COMPUTER PROGRAM

Rd. no.	Deflections		Range meters	Hob meters	Erms-Az mils	Erms-El mils	Towers
	mils	meters					
2A3	F6.1	F6.1	F8.1	F7.1	F8.3	F8.3	ALL
2A3	F6.1	F6.1	F8.1	F7.1	F8.3*	F8.3	OMITTING TOWER J
2A3	F6.1	F6.1	F8.1	F7.1	F8.3	F8.3*	OMITTING TOWER J'

\* Line printed only if value is found significant in outlier subroutine

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APPENDIX B:  
LISTING OF LEAST-SQUARES COMPUTER PROGRAM  
WRITTEN FOR ABERDEEN PROVING GROUND, MD, BY NEAL ROBERTS



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C   PROGRAM TO FIND RANGE, DEFLECTION, AND HEIGHT OF BURST
C   OF FIRED ARTILLERY PROJECTILES BY USING A LEAST
C   SQUARES TECHNIQUE WHICH MINIMIZES ANGULAR ERROR.
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION AZ(201,7),ALX(201,7),AZD(201,7),AZM(201,7)
      DIMENSION EZD(201,7),EZM(201,7),X(7),Y(7),Z(7)
      DIMENSION AZMLS(201,7),EZMLS(201,7),ISB(7),CNT(3),PT(3)
      DIMENSION RNG(7,201),XCNT(7),YCNT(7),ZCNT(7)
      DIMENSION ERROR(7),ERRORE(7)
      DIMENSION ID1(201),ID2(201)
      WRITE(6,700)
      N=0
1    READ(5,501) XT,YT,ZT,ITOWER,IP
      IF(IP.EQ.1H ) GO TO 2
      X(ITOWER)=XT
      Y(ITOWER)=YT
      Z(ITOWER)=ZT
      N=N+1
      GO TO 1
2    READ(5,502) X(7),Y(7),Z(7),AZDG,AZMG
      AZ(1,7)=((AZDG+AZMG/60.D0)-35.D0)*.017453293
      IRDG=0
      DO 70 J=1,N
      K=1
      DO 70 I=1,200
      GO TO (30,60) K
30   READ(5,1030) AZD(I,J),AZM(I,J),EZD(I,J),EZM(I,J),ID1(I),ID2(I)
32   IF(AZD(I,J).EQ.-999.D0) GO TO 60
33   IF(AZD(I,J).NE.+999.D0) GO TO 50
34   IF(IRDG-I) 35,40,40
35   IRDG=I
40   K=2
      GO TO 60
50   IF(EZD(I,J).EQ.-999.D0) GO TO 60
      AZ(I,J)=((AZD(I,J)+AZM(I,J)/60.D0)-35.D0)*.017453293
      ALX(I,J)=(EZD(I,J)+EZM(I,J)/60.D0)*.017453293
      GO TO 70
60   AZ(I,J)=99999.D0
      ALX(I,J)=-999.D0
70   CONTINUE
      IRDG=IRDG-1
80   DO 81 I=1,IRDG
81   AZ(I,7)=AZ(1,7)
C   WRITE HEADINGS
      WRITE(6,701)
      WRITE(6,702)
      DO 280 I=1,IRDG
      NHR=1
      J=1
      DO 90 K=1,N
      IF(AZ(I,K).EQ.99999.D0) GO TO 90
      NHR=NHR+1
      ISB(J)=K
      J=J+1
90   CONTINUE

```

```

      GO TO (274,110,120,130,130,130,130),NHR
274 WRITE(6,1000) ID1(I),ID2(I)
      GO TO 280
110 ISB(2)=7
120 CALL POINT(AZ,I,ISB,X,Y,PT)
      CNT(1)=PT(1)
      CNT(2)=PT(2)
      CALL RANGE(X(7),Y(7),AZ(1,7),CNT,RN,DEFL,DEFLM)
      CNT(1)=PT(1)
      CNT(2)=PT(2)
      IF(ISB(2).NE.7) GO TO 121
      KK=ISB(1)
      CALL RANGE(X(KK),Y(KK),AZ(1,7),CNT,RNG(KK,I),DEFL,DEFLM)
      DZ=RNG(KK,I)*TAN(ALX(I, KK))
      ZN=Z(KK)+DZ
      GO TO 122
121 KK1=ISB(1)
      KK2=ISB(2)
      CALL RANGE(X(KK1),Y(KK1),AZ(1,7),CNT,RNG(KK1,I),DEFL,DEFLM)
      CALL RANGE(X(KK2),Y(KK2),AZ(1,7),CNT,RNG(KK2,I),DEFL,DEFLM)
      DZ1=RNG(KK1,I)*TAN(ALX(I, KK1))
      DZ2=RNG(KK2,I)*TAN(ALX(I, KK2))
      ZN1=Z(KK1)+DZ1
      ZN2=Z(KK2)+DZ2
      ZN=(ZN1+ZN2)/2.
122 WRITE(6,1002) ID1(I),ID2(I),DEFLM,DEFL,RN,ZN
      GO TO 280
130 NT=NHR-1
      CALL POINT(AZ,I,ISB,X,Y,PT)
      ISB(NHR)=ISB(NT)+1
      CNT(2)=PT(2)
      CNT(1)=PT(1)
      KK=ISB(1)
      CALL RANGE(X(KK),Y(KK),AZ(1,7),CNT,RNG(KK,I),DEFL,DEFLM)
      DZ=RNG(KK,I)*TAN(ALX(I, KK))
      PT(3)=- (Z(KK)+DZ)
      DO 140 IT=1,NHR
      CNT(3)=PT(3)
      CNT(2)=PT(2)
      CNT(1)=PT(1)
      ITER=ISB(IT)
      CALL LSTQR(CNT,ERMS,ITER,I,ISB,AZ,NT,X,Y,Z,ERMSEL,ALX,IQ,ID1,ID2)
      IF(IQ.EQ.1) GO TO 280
      XCNT(ITER)=CNT(1)
      YCNT(ITER)=CNT(2)
      ZCNT(ITER)=CNT(3)
      ERROR(ITER)=ERMS
      ERRORE(ITER)=ERMSEL
140 CONTINUE

```

```

JALL=ISB(NHR)
ERMS=ERROR(JALL)
CNT(1)=XCNT(JALL)
CNT(2)=YCNT(JALL)
CALL RANGE(X(7),Y(7),AZ(1,7),CNT,RN,DEFL,DEFLM)
ERMSE=ERRORE(JALL)
HOB=-ZCNT(JALL)
WRITE(6,1003) ID1(I),ID2(I),DEFLM,DEFL,RN,HOB,ERMS,ERMSE
IF(ERROR(JALL).EQ.0.AND.ERRORE(JALL).EQ.0) GO TO 280
IF(ERROR(JALL).EQ.0) GO TO 150
CALL MODF(ERROR,ISB,NHR,NT,ITOWER,VAR1,VAR,III)
IF(III.EQ.0) GO TO 150
CALL OUTLY(VAR1,VAR,SIG,ITEST,NHR)
IF(ITEST.EQ.0) GO TO 150
J=ITOWER
CNT(1)=XCNT(J)
CNT(2)=YCNT(J)
ERMS=ERROR(J)
ERMSE=ERRORE(J)
HOB=-ZCNT(J)
CALL RANGE(X(7),Y(7),AZ(1,7),CNT,RN,DEFL,DEFLM)
WRITE(6,1004) ID1(I),ID2(I),DEFLM,DEFL,RN,HOB,ERMS,ERMSE,J,SIG
150 IF(ERRORE(JALL).EQ.0) GO TO 280
CALL MODF(ERRORE,ISB,NHR,NT,ITOWER,VAR1,VAR,III)
IF(III.EQ.0) GO TO 280
CALL OUTLY(VAR1,VAR,SIG,ITEST,NHR)
IF(ITEST.EQ.0) GO TO 280
J=ITOWER
CNT(1)=XCNT(J)
CNT(2)=YCNT(J)
ERMS=ERROR(J)
ERMSE=ERRORE(J)
HOB=-ZCNT(J)
CALL RANGE(X(7),Y(7),AZ(1,7),CNT,RN,DEFL,DEFLM)
WRITE(6,1005) ID1(I),ID2(I),DEFLM,DEFL,RN,HOB,ERMS,ERMSE,J,SIG
280 CONTINUE
STOP
501 FORMAT(3F10.2,47X,I1,1X,A1)
502 FORMAT(3F10.2,2F10.1)
700 FORMAT('1')
701 FORMAT('0','RD.NO.',T12,'DEFLECTIONS',T30,'RANGE',T40,'HOB',T55,'E
1RMS-AZ',T65,'ERMS-EL',T80,'TOWERS')
702 FORMAT(1H ,T11,'MILS',T19,'METERS',T39,'METERS',T57,'MILS',T67,'MI
1LS')
1000 FORMAT('0',A3,A3)
1002 FORMAT('0',2A3,T9,F6.1,T19,F6.1,T28,F8.1,T38,F7.1)
1003 FORMAT('0',2A3,T9,F6.1,T19,F6.1,T28,F8.1,T38,F7.1,T54,F8.3,T64,F8.
13,T82,'ALL')
1004 FORMAT(1H ,2A3,T9,F6.1,T19,F6.1,T28,F8.1,T38,F7.1,T54,F8.3,T62,'*'
1,T64,F8.3,T80,'OMITING TOWER ',I1,' (SIG. AT ',F4.2,' LEVEL)')
1005 FORMAT(1H ,2A3,T9,F6.1,T19,F6.1,T28,F8.1,T38,F7.1,T54,F8.3,T64,F8.
13,T72,'*',T80,'OMITING TOWER ',I1,' (SIG. AT ',F4.2,' LEVEL)')
1030 FORMAT(2F7.2,2F7.2,2X,2A3)
END

```

```
SUBROUTINE POINT(AZ, I, ISB, X, Y, PT)
IMPLICIT REAL*8(A-H, O-Z)
DIMENSION AZ(201, 7), ISB(7), X(7), Y(7), PT(3)
JISC=ISB(1)
KISC=ISB(2)
A=TAN(AZ(I, JISC))
B=TAN(AZ(I, KISC))
PT(1)=(X(JISC)*A-Y(JISC)+Y(KISC)-X(KISC)*B)/(A-B)
PT(2)=(PT(1)-X(KISC))*B+Y(KISC)
RETURN
END
```

```
SUBROUTINE RANGE(X,Y,AZ,CNT,RNG,DEFL,DEFLM)
IMPLICIT REAL*8(A-H,O-Z)
DIMENSION CNT(3)
RNG=CNT(1)-X
DEFL=CNT(2)-Y
CALL ATNSR(DEFL,RNG,BETA,1)
DEFLM=BETA-AZ
10 IF(DEFLM+3.14159265) 30,30,20
20 IF(DEFLM-3.14159265) 50,40,40
30 DEFLM=DEFLM+6.28318531
GO TO 10
40 DEFLM=DEFLM-6.28318531
GO TO 10
50 RNG=RNG/COS(BETA)
DEFL=RNG*SIN(DEFLM)
DEFLM=1018.59164*DEFLM
RETURN
END
```

```
SUBROUTINE ATNSR(A,B,C,L)
IMPLICIT REAL*8(A-H,O-Z)
P=3.14159265
C=ATAN(A/B)
IF(A) 10,40,40
10 IF(B) 20,30,30
20 GO TO (21,22),L
21 C=P+C
GO TO 50
22 C=C-2.*P
GO TO 50
30 GO TO (31,50),L
31 C=2.*P+C
GO TO 50
40 IF(B) 20,50,50
50 RETURN
END
```

```

SUBROUTINE LSTQR(CNT,ERMS,ITER,I,ISB,AZ,NT,X,Y,Z,ERMSEL,ALX,IQ,ID1
1, ID2)
IMPLICIT REAL*8(A-H,O-Z)
DIMENSION AZ(201,7),ALX(201,7),CNT(3),ISB(7),X(7),Y(7),Z(7)
DIMENSION DAZ(6),DAZX(6),DAZY(6),RNG(7,201)
DIMENSION DEL(6),DELX(6),DELY(6),DELZ(6),ID1(201),ID2(201)
ICOUNT=1
IQ=0
183 ICOUNT=ICOUNT+1
IF(ICOUNT.NE.201) GO TO 10
WRITE(6,1) ID1(I),ID2(I)
1 FORMAT(1X,2A3,5X,'LSTQR SUBROUTINE DID NOT CONVERGE IN 200 ITERATI
IONS')
IQ=1
GO TO 9
10 DO 190 II=1,NT
J=ISB(II)
IF(J.EQ.ITER) GO TO 190
YC=CNT(2)-Y(J)
XC=CNT(1)-X(J)
CALL ATNSR(YC,XC,ANGLE,1)
DAZ(II)=ANGLE-AZ(I,J)
184 IF(DAZ(II)+3.14159265) 186,186,185
185 IF(DAZ(II)-3.14159265) 189,188,188
186 DAZ(II)=DAZ(II)+6.28318531
GO TO 184
188 DAZ(II)=DAZ(II)-6.28318531
GO TO 184
189 CONTINUE
DAZX(II)=-YC/(XC**2+YC**2)
DAZY(II)=XC/(XC**2+YC**2)
190 CONTINUE
N=0
SERMS=0.
DO 191 II=1,NT
J=ISB(II)
IF(J.EQ.ITER) GO TO 191
N=N+1
SERMS=SERMS+DAZ(II)**2
191 CONTINUE
ERMS=1018.59164*SQRT(SERMS/FLOAT(N))
TM1=0.
TM2=0.
TM3=0.
TM4=0.
TM5=0.
TM6=0.
DO 192 II=1,NT
J=ISB(II)
IF(J.EQ.ITER) GO TO 192
TM1=TM1+DAZ(II)*DAZX(II)
TM2=TM2+DAZX(II)**2
TM3=TM3+DAZX(II)*DAZY(II)
TM4=TM4+DAZ(II)*DAZY(II)
TM5=TM5+DAZX(II)*DAZY(II)
TM6=TM6+DAZY(II)**2
192 CONTINUE

```



```

DY=(TM1*TM5-TM4*TM2)/(TM3*TM5-TM6*TM2)
DX=(TM1-TM3*DY)/TM2
DO 200 II=1,NT
J=ISB(II)
IF(J.EQ.ITER) GO TO 200
YC=CNT(2)-Y(J)
XC=CNT(1)-X(J)
ZC=CNT(3)+Z(J)
CALL RANGE(X(J),Y(J),AZ(1,7),CNT,RNG(J,I),DEFL,DEFLM)
ANGLE=ATAN(ZC/RNG(J,I))
DEL(II)=-ANGLE-ALX(I,J)
194 IF(DEL(II)+3.14159265) 196,196,195
195 IF(DEL(II)-3.14159265) 199,198,198
196 DEL(II)=DEL(II)+6.28318531
GO TO 194
198 DEL(II)=DEL(II)-6.28318531
GO TO 194
199 CONTINUE
D1=(XC**2+YC**2+ZC**2)
D2=SQRT(XC**2+YC**2)
DELX(II)=(-XC*ZC)/(D1*D2)
DELY(II)=(-YC*ZC)/(D1*D2)
DELZ(II)=D2/D1
200 CONTINUE
N=0
SERMS=0.
DO 201 II=1,NT
J=ISB(II)
IF(J.EQ.ITER) GO TO 201
N=N+1
SERMS=SERMS+DEL(II)**2
201 CONTINUE
ERMSEL=1018.59164*SQRT(SERMS/FLOAT(N))
TM1=0.
TM2=0.
TM3=0.
TM4=0.
DO 202 II=1,NT
J=ISB(II)
IF(J.EQ.ITER) GO TO 202
TM1=TM1+DEL(II)*DELZ(II)
TM2=TM2+DELX(II)*DELZ(II)
TM3=TM3+DELY(II)*DELZ(II)
TM4=TM4+DELZ(II)**2
202 CONTINUE
DZ=(TM1-TM2*DX-TM3*DY)/TM4
IF(ABS(DX).LE..1.AND.ABS(DY).LE..1.AND.ABS(DZ).LE..1) GO TO 9
CNT(2)=CNT(2)-DY
CNT(1)=CNT(1)-DX
CNT(3)=CNT(3)+DZ
GO TO 183
9 RETURN
END

```

```

SUBROUTINE OUTLY(ERMS,ERROR,SIG,ITEST,NT)
IMPLICIT REAL*8(A-H,O-Z)
DIMENSION F99(8),F975(8),F95(8),F90(8)
DATA F99/.0,.0,.0001,.0100,.0442,.0928,.1447,.1948/
DATA F975/.0,.0,.0007,.0248,.0808,.1453,.2066,.2616/
DATA F95/.0,.0,.0027,.0494,.1270,.2032,.2696,.3261/
DATA F90/.0,.0,.0109,.0975,.1984,.2826,.3503,.4050/
F=ERMS/ERROR
IF(F.LE.F99(NT)) GO TO 10
IF(F.LE.F975(NT)) GO TO 20
IF(F.LE.F95(NT)) GO TO 30
IF(F.LE.F90(NT)) GO TO 40
ITEST=0
RETURN
10 SIG=.99
ITEST=1
RETURN
20 SIG=.975
ITEST=1
RETURN
30 SIG=.95
ITEST=1
RETURN
40 SIG=.90
ITEST=1
RETURN
END

```

```

SUBROUTINE MODF(ERROR, ISB, NHR, NT, ITOWER, VAR1, VAR, III)
IMPLICIT REAL*8(A-H, O-Z)
DIMENSION ERROR(7), ISB(7)
TEMP=ERROR(NHR)
X1=ERROR(NHR)
DO 160 IT=1, NT
J=ISB(IT)
ERMS=ERROR(J)
IF(ERMS.GE.TEMP) GO TO 160
ITOWER=J
X1=ERROR(J)
TEMP=ERROR(J)
160 CONTINUE
IF(X1.GE.ERROR(NHR)) GO TO 169
SUM=0.D0
DO 162 IT=1, NHR
J=ISB(IT)
SUM=SUM+ERROR(J)
162 CONTINUE
AVG=SUM/FLOAT(NHR)
SUM=0.D0
DO 164 IT=1, NHR
J=ISB(IT)
IF(J.EQ.ITOWER) GO TO 164
SUM=SUM+ERROR(J)
164 CONTINUE
AVG1=SUM/FLOAT(NT)
VAR=0.D0
DO 166 IT=1, NHR
J=ISB(IT)
VAR=VAR+(ERROR(J)-AVG)**2
166 CONTINUE
VAR1=0.D0
DO 168 IT=1, NHR
J=ISB(IT)
IF(J.EQ.ITOWER) GO TO 168
VAR1=VAR1+(ERROR(J)-AVG1)**2
168 CONTINUE
III=1
GO TO 170
169 III=0
170 RETURN
END

```

APPENDIX C:  
SAMPLE INPUT TO LEAST-SQUARES COMPUTER PROGRAM

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3657.607	12801.626	32.13
3868.530	13870.487	13.3
3754.335	13094.383	4.77
2883.79	11998.31	12.13

1 T  
2 T  
3 T  
4 T

3812.273	12475.803	41.0	26.
34.	22.	18.	51.
34.	23.	17.	45.
34.	25.	18.	46.
34.	18.	17.	41.
34.	11.	5.	35.
34.	17.	5.	09.
34.	05.	5.	35.
34.	17.	5.	08.
+999.			
11.	08.	19.	07.
9.	54.	18.	01.
11.	13.	19.	05.
9.	42.	17.	42.
10.	52.	6.	09.
11.	19.	6.	37.
10.	36.	6.	01.
11.	03.	5.	32.
+999.			
26.	57.	20.	04.
27.	28.	18.	50.
27.	52.	19.	45.
27.	24.	18.	40.
27.	42.	6.	45.
27.	57.	5.	55.
27.	32.	6.	35.
27.	45.	5.	50.
+999.			
47.	37.	14.	48.
47.	55.	13.	38.
47.	35.	14.	56.
48.	03.	13.	41.
47.	26.	4.	35.
47.	24.	4.	19.
47.	33.	4.	39.
47.	35.	4.	17.
+999.			

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APPENDIX D:  
SAMPLE OUTPUT FROM LEAST-SQUARES COMPUTER PROGRAM



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RD. NO.	DEFLECTIONS MILS	DEFLECTIONS METERS	RANGE	HOB METERS	ERMS-AZ MILS	ERMS-EL MILS	TOWERS
11	-0.8	-2.0	2548.5	953.3	7.283	1.328	ALL
11	4.4	10.9	2553.7	951.7	0.274*	0.428	OMITTING TOWER 3 (SIG. AT 0.95 LEVEL)
11	4.4	10.9	2553.7	951.7	0.274	0.428*	OMITTING TOWER 3 (SIG. AT 0.98 LEVEL)
12	8.9	21.3	2428.3	853.2	1.266	1.702	ALL
12	10.8	25.6	2417.4	851.5	0.802	0.856*	OMITTING TOWER 4 (SIG. AT 0.90 LEVEL)
13	3.8	9.6	2561.6	951.7	0.843	1.674	ALL
13	4.4	11.1	2562.2	954.0	0.074*	1.439	OMITTING TOWER 3 (SIG. AT 0.95 LEVEL)
14	9.9	23.5	2405.8	839.5	0.472	0.885	ALL
14	9.4	22.2	2407.4	838.8	0.061*	0.570	OMITTING TOWER 1 (SIG. AT 0.95 LEVEL)
15	0.5	1.2	2547.1	303.4	0.292	2.796	ALL
16	0.9	2.4	2587.4	293.7	0.273	8.210	ALL
16	0.8	1.9	2587.2	299.6	0.016*	8.713	OMITTING TOWER 3 (SIG. AT 0.95 LEVEL)
16	0.8	2.0	2591.9	279.9	0.208	0.613*	OMITTING TOWER 2 (SIG. AT 0.99 LEVEL)
17	0.8	2.0	2518.1	297.2	0.433	1.488	ALL
18	2.6	6.5	2550.1	274.3	0.853	0.791	ALL

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**APPENDIX E:  
SUMMARIZED DATA OUPUT TO TRIANGULATION COMPUTER PROGRAM USING SAMPLE  
DATA INPUT OF APPENDIX C**

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RD.NO.	DEFLECTIONS		RANGE METERS	AVERAGE HOB METERS
	MILS	METERS		
11	4.3	10.9	2551.5	952.9
12	7.7	18.3	2433.0	853.9
13	4.4	11.1	2562.7	952.9
14	9.4	22.3	2407.5	840.2
15	1.0	2.6	2543.3	302.1
16	0.8	1.9	2587.1	292.8
17	0.2	0.5	2520.9	297.5
18	3.5	8.6	2530.4	273.0

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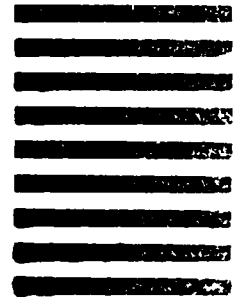


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