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A COMPUTER PROGRAM FOR THE IDENTIFICATION OF HELICOPTER IMPULSIVE NOISE SOURCES

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1. SUMMARY

A computer program, named INSL, is written for the calculation of the source location of impulsive noise. The main program is listed in Appendix 1. The algorithm is basically solving the triangulation equation:

$$r^4 + A_3(\psi)r^3 + A_2(\psi) + A_1(\psi)r + A_0(\psi) = 0 \qquad (1)$$

where

$$A_0(\psi) = [E - (T - \tfrac{\psi}{\omega})\ U_0F]^2 - E\ (T - \tfrac{\psi}{\omega})^2\ C^2$$

$$A_1(\psi) = 2\ [2A - (T_1 - \tfrac{\psi}{\omega})\ U_oB]\ [E - (T - \tfrac{\psi}{\omega})\ U_oF]$$
$$-2A(T - \tfrac{\psi}{\omega})^2\ C^2$$

$$A_2(\psi) = [2A - (T - \tfrac{\psi}{\omega})\ U_0\ B]^2 + 2[E - (T - \tfrac{\psi}{\omega})\ U_oF]^2$$
$$- (T - \tfrac{\psi}{\omega})^2\ C^2$$

$$A_3(\psi) = 2\ [2A - (T - \tfrac{\psi}{\omega})\ U_0B]$$

$$A = (-y_1 \sin\psi + g \sin\alpha_s \cos\psi + x_1 \cos\psi) \cos\beta_0$$
$$+ (g \cos\alpha_s + z_1) \sin\beta_0$$

$$E = x_1^{\ 2} + y_1^{\ 2} + z_1^{\ 2} + g\ (g + 2x_1 \sin\alpha_s + 2z_1 \cos\alpha_s)$$

$$F = -g \sin\alpha_s - x_1$$

$$B = -\cos\beta_0 \cos\psi$$

$$C = 1052 + 1.143\ \mathrm{TEM}$$

$$\beta_0 = \beta - \alpha_s \cos\psi$$

$$\beta = a_o - a_{1s} \cos\psi - b_{1s} \sin\psi$$

and

r, ψ = Coordinates of source in ft and radian, respectively

T = Time between acoustical signature and $\psi = 0$ index

U_0 = Tunnel velocity in ft/sec

ω = Rotor rotational velocity in Rad/sec

g = Shaft length above pivot in ft

α_s = Shaft angle of attack in radian

a_o = Coning angle in radian

a_{1s} = Longitudinal flapping coefficient

b_{1s} = Lateral flapping coefficient

TEM = Tunnel temperature in deg F

x, y, z = Coordinates of microphone in ft

The coordinates and symbols are illustrated in Figure 1. For detail formulation and discussion of the triangulation techniques, one should be referred to NASA CR 151996.

For each azimuthal location ψ, a library subroutine is used to solve this fourth order equation, and all four roots are obtained. The algorithm picks out the meaningful roots, i.e., those which are inside the rotor radius, then these roots are double-checked to ensure their accuracy. The procedures are then repeated for a different value of ψ. Variable step sizes of ψ are used to accelerate the computations.

The computer program is written in FORTRAN for CDC 7600. The inputs are rotor operating conditions and the time intervals (T) between rotor 1/rev index and impulsive noises as measured by different microphones. The outputs are the possible noise source locations in terms of rotor radial and azimuthal coordinates. Typical computer time for a run of six microphone measurements is 1.5 sec, and the cost is about 12 cents for the CDC 7600 at NASA Ames Research Center.

2. ALGORITHM

The block diagram is shown in Figure 2. The flow chart is shown in Figure 3. The coefficients of equation (1) are first calculated at an azimuthal angle ψ based on the input data. A library subroutine ZPOLR is then called to solve equation (1) for radial location r. Four roots are obtained. They may be complex, real or mixed. Only positive real roots whose value are within rotor radius are meaningful, and those values are automatically selected. The value of ψ is then decreased by one step, and the calculations proceed.

Two step sizes of ψ are used. A coarse step size is used initially until a meaningful r is obtained. The azimuth, ψ, is then backed up one step size, and calculation proceeds with a fine step size. After a succession of calculation, there is a value of ψ beyond which no meaningful r is obtained. The calculations with fine step size persist beyond this point for several steps which is controlled as an input. If there is still no meaningful r obtained, the calculation proceeds with coarse steps until the range of ψ is reached, or until a meaningful r is obtained again. In the former case, the calculations re-initiate for the next microphone measurement. In the latter case, the step size is changed again in the manner previously described.

The scheme of variable step size can save a large amount of computer time. Typically, the course step is 2 degrees and the fine step is 1 degree for the first calculation. Depending on microphone locations and other parameters, source lines extend either from the outer edge of the disk to the rotor hub or terminate at the middle. When calculated results show source lines which terminate at the middle of the rotor disk, it may be real or may be due to the improper step size in ψ. A smaller step size should then be used to recalculate for the source line within this rather small range of azimuth. For example, some calculations with 0.1 degree step size within an azimuthal range of 2° have been performed to obtain results shown in NASA CR 151996. If the source lines really terminate in the middle of the rotor disc, subsequent reduction of step size will not change this result.

The range of azimuth for calculation should be noted. For two bladed rotors, there are two acoustical impulses for each rotor period which is marked by 1/rev index. The source location can be either before $\psi = 0$ (1/rev index) or after it. The azimuth range of calculation should cover both positive and negative azimuth. Either of the two acoustical impulses in a period can be chosen for calculation, although only one yields meaningful results. This situation must be resolved by physical arguments based on the characteristics of the noise source.

3. DATA CARDS

A total of eleven (11) input data cards are used.

Card Number	Format	Remarks
1	2A10	20 alphameric characters used for labeling of output
2	F10.3	Rotor angular velocity in rad/sec
	F10.4	Rotor shaft tilt angle in rad/sec, positive shaft tilt aft
	F10.4	Tip path plane angle in radians, positive leading edge up
	F10.1	Tunnel temperature in ^{o}F
	F10.3	Tunnel velocity in ft/sec
	I10	Number of microphones. Any number up to 6 can be specified
3	6F10.4	X-coordinates of microphones, in ft
4	6F10.4	Y-coordinates of microphones, in ft
5	6F10.4	Z-coordinates of microphones, in ft
6	6F10.4	Time (in sec) between the 1/rev index and impulsive noise as measured by microphones. The values should be consistent with the sequence of microphones specified in Cards 3,4, and 5
7	F10.4	Coarse step size of ψ in radius
	F10.4	Fine step size of ψ in radius

8	F10.4	Criterion of selecting real roots
	F10.4	Criterion of distinguishing double roots
	F10.4	Criterion in the double-check
	I10	Number of calculation with fine increment after a succession of obtaining meaningful r
9	F10.4	Largest value of azimuth ψ in radians
	F10.4	Smallest value of azimuth ψ in radians
10	F10.2	Length of shaft in feet
	F10.4	Coning angle in radians
11	F10.4	Radius of rotor in feet

4. EXAMPLE

As an example, program INSL is applied to a data point of high speed rotor noise measured in the 40- by 80-Foot Wind Tunnel at the NASA Ames Research Center.

The rotor, test conditions, and input criteria are tabulated below:

Rotor and Test Conditions

Number of blades	2
Blade precone angle	2 deg (0.0349 rad.)
Rotor radius	24 ft (7.315 m)
Blade chord	1.75 ft (0.5334 m)
Blade twist	-8 deg
Airfoil	NACA 0012
Hub articulation	teetering
Shaft height above the pivot (See Fig. 1)	6.94 ft (2.115 m)
Tip speed ratio, $V/\Omega R$	0.3
Rotor rotational speed	327 RPM
Rotation tip Mach number	0.747
Tip speed	821.8 ft/s (250.5 m/s)
Shaft angle of attack	0 deg
Tip path plane	0 deg
Tunnel temperature	70 F (21 C)
Tunnel speed	247.1 fps (75.32 m/sec, 146.4 knots)

Microphones

Number of microphones 6

Microphone locations

X (ft)	X (m)	Y (ft)	Y (m)	Z (ft)	Z (m)
68.24	20.80	-20	6.096	8.06	2.457
6.99	2.131	5.	1.524	1.25	.3810
68.58	20.90	0	0	8.07	2.460
13.84	-4.215	10.92	3.328	-1.08	.3292
68.83	20.98	20.	6.096	8.08	2.463
12.41	3.783	12.83	3.911	7.	2.134

Time between 1/rev index and acoustical index (in sec) .1390, .0565, 1300, .0235, .1255, .0610

Input Criteria

Coarse step	2 deg (.0349 radian)
Fine step	1 deg (.0175 radian)
Criterion of real root	1
Criterion of double root	.5
Double-check criterion	.001
Largest ψ	6.94 rad
Smallest ψ	-3.1416 rad

The input data deck to program INSL is shown in Appendix 2. The printout of the calculation is shown in Appendix 3. The first portion is the printout of input data. It then proceeds to print the results of the calculations. The first two columns are the coordinates of source line in terms of their radial location r and azimuth location ψ. DIS is the distance between source and microphone. TIME is the time for sound to travel from source to microphone, including effects of tunnel wind. CTIME is the calculated time between 1/rev and acoustical impulse and should be consistent with input time (T). A plot of source lines in this sample calculation is shown in Figure 4.

APPENDIX 1

```
C      THIS PROGRAM IS CALLED INSL (IMPULSIVE NOISE SOURCE LOCATING),
C      AND WRITTEN BY YING-CHIEH ALBERT LEE.
C      THIS PROGRAM IS TO CALCULATE THE NOISE SOURCE LOCATIONS OF
C      HELICOPTER ROTOR BLADE SLAP.  THE TUNNEL SPEED EFFECT ON SOUND
C      SPEED WAS TAKEN INTO ACCOUNT.  THE INPUT DATA ARE THE LOCATIONS
C      OF M MICROPHONE AND THE TIME BETWEEN 1/REV PULSE AND ACOUSTICAL
C      SIGNALS, IN ADDITION TO ROTOR PARAMETERS.  THE OUTPUT IS THE
C      NOISE SOURCE IN TERMS OF ITS AZIMUTHAL (SI) AND RADIAL (R)
C      POSITIONS.  THE MEANING OF SYMBOLS ARE AS FOLLOWS:
C      G IS THE SHAFT LENGTH IN FEET
C      AM IS THE ANGULAR VELOCITY OF ROTOR IN RAD/SEC
C      AS IS THE SHAFT TILT ANGLE IN RADIANS
C      AT IS THE TIP PATH PLANE ANGLE IN RADIANS
C      AZ IS THE PRE-CONED ANGLE OF THE TEETERING ROTOR IN RADIANS
C      TEM IS THE TEMPERATURE IN DEGREE-F
C      U IS THE TUNNEL SPEED IN FT/SEC
C      M IS THE NUMBER OF MICROPHONE
C      X,Y,Z ARE THE MICROPHONE LOCATION, IN FT
C      THE COORDINATE ORIGIN IS AT THE MID-POINT BETWEEN BALL CENTERS
C      T IS THE TIME BETWEEN 1/REV AND ACOUSTICAL PULSE, IN SEC
C      THETA IS THE ANGLE BETWEEN THE VECTOR FROM MICOPHONE TO SOUND
C      SOURCE AND TUNNEL VELOCITY VECTOR
C      DS IS THE AZIMUTHAL ANGULAR INCREMENT, IN RADIANS
C      DS1 IS THE FINE AZIMUTHAL ANGULAR INCREMENT, IN RADIANS
C      EP1 IS THE ACCURACY OF RADIAL LOCATION, IN FT
C      EP2 IS THE ACCURACY OF AZIMUTHAL ANGLE, IN RADIANS
C      EP3 IS THE CHECK FOR REAL ROOTS
C      EP4 IS THE CHECK FOR DOUBLE ROOT
C      EP5 IS THE CHECK IN DOUBLE-CHECK CALCULATIONS
C      KIN IS THE NUMBER OF TIMES OF FINE INCREMENT CALCULATION AFTER
C      THE END OF SUCCESS OF OBTAINING ACCURATE ROOTS
C      SII IS THE INITIAL AZIMUTHAL ANGLE
C      SIF IS THE FINAL AZIMUTHAL ANGLE
C      DIS IS DISTANCE BETWEEN SOURCE AND MICROPHONE,
C      TIME IS THE SOUND TRAVELING TIME FROM SOURCE TO MICROPHONE,
C      INCLUDING THE WIND EFFECT.
C      CTIME IS THE CALCULATED TIME BETWEEN 1/REV AND ACOUSTICAL IMPULSE
       COMPLEX ZI
       DIMENSION X(6),Y(6),Z(6),T(6),A(6),ZI(6),R(6,550),ANG(6,550),C(4),
      1KA(5),CN(5),CP(5),CI(5),TEST(2),YS(6)
     1 FORMAT (F10.3,F10.4,F10.4,F10.1,F10.3,I10)
     2 FORMAT (6F10.4)
     3 FORMAT (F10.4,F10.4,F10.4,F10.4)
     4 FORMAT (1H ,2HX=,6F8.2)
```

```
 5 FORMAT (1H ,2HY=,6F8.2)
 6 FORMAT (1H ,2HZ=,6F8.2)
 7 FORMAT (1H ,2A10)
 8 FORMAT (F10.2,F10.4)
 9 FORMAT (F10.4)
11 FORMAT (1H ,7HRADIUS=,F10.4)
12 FORMAT (1H ,2HR=,F5.1,7H   ANG=,F8.4,3H  =,F8.2,3HDEG,5H    I=,
  1I2,5H   K=,I2,7H   DIS=,F5.1,8H   TIME=,F8.4,
  29H   CTIME=,F8.4)
14 FORMAT (1H ,2HG=,F5.2,3HFT ,3HAM=,F9.4,8HRAD/SEC ,3HAS=,F8.4,
  14HRAD ,3HAT=,F8.4,4HRAD ,3HAZ=,F8.4,4HRAD ,5H TEM=,F6.2,2HF ,2HU=,
  2F8.2,4HFPS ,I3,6H MIKES)
16 FORMAT (1H ,2HT=,6F8.4)
17 FORMAT (1H ,3HDS=,F7.4,3HRAD,6H  DSI=,F7.4,3HRAD,6H  EP1=,F7.4,
  12HFT,6H  EP2=,F7.4,3HRAD)
18 FORMAT (1H ,14HEND OF I=PRINT///)
20 FORMAT (F10.4,F10.4,F10.4,I10)
21 FORMAT (1H ,4HEP3=,F10.4,6H  EP4=,F10.4,6H  EP5=,F10.4,6H  KIN=,
  1I5//)
22 FORMAT (1H ,I2,7H  ROOTS)
23 FORMAT (1H ,21HEND OF MULTIPLE ROOTS/)
24 FORMAT (2F10.4)
25 FORMAT (1H ,4HSII=,F10.4,6H  SIF=,F10.4)
26 FORMAT (2A10)
   READ(5,26) TEST
   READ (5,1) AM,AS,AT,TEM,U,M
   READ (5,2) (X(I),I=1,M)
   READ (5,2) (Y(I),I=1,M)
   READ (5,2) (Z(I),I=1,M)
   READ (5,2) (T(I),I=1,M)
   READ (5,3) DS,DSI,EP1,EP2
   READ (5,20) EP3,EP4,EP5,KIN
   READ (5,24) SII,SIF
   READ (5,8) G,AZ
   READ  (5,9) RADIUS
   WRITE(6,7)TEST
   WRITE (6,11) RADIUS
   WRITE (6,14) G,AM,AS,AT,AZ,TEM,U,M
   WRITE (6,4) (X(I),I=1,M)
   WRITE (6,5) (Y(I),I=1,M)
   WRITE (6,6) (Z(I),I=1,M)
   WRITE(6,16) (T(I),I=1,M)
   WRITE (6,25) SII,SIF
   WRITE (6,17) DS,DSI,EP1,EP2
   WRITE (6,21) EP3,EP4,EP5,KIN
```

```
      DO 100 I=1,M
      YS(I)=Y(I)
      Y(I)=X(I)
      X(I)=YS(I)
  100 Z(I)=-Z(I)
      DO 10 I=1,M
      KO=0
      K=0
      SI=STI
  150 AP=(-X(I)*SIN(SI)+G*SIN(AS)*COS(SI)+Y(I)*COS(SI))*COS(AZ-AT*
     1COS(SI))+(G*COS(AS)-Z(I))*SIN(AZ-AT*COS(SI))
      B=-COS(AZ-AT*COS(SI))*COS(SI)
      S=1052.+1.1434*TEM
      D=T(I)-SI/AM
      E=X(I)**2+Y(I)**2+Z(I)**2+G*(G+2.*Y(I)*SIN(AS)-2.*Z(I)*COS(AS))
      F=-G*SIN(AS)-Y(I)
      C1=2.*AP-D*U*B
      C2=E-D*U*F
      A(1)=1.
      A(2)=2.*C1
      D1=D**2*S**2
      A(3)=C1**2+2.*C2-D1
      A(4)=2.*C1*C2-2.*AP*D1
      A(5)=C2**2-E*D1
      CALL ZPOLR (A,4,ZI,IER)
C     FOUND ZEROS OF 4TH ORDER POLYNOMIAL
C
C     START TO SELECT THE REAL ZERO
      J=0
      DO 50 I1=1,4
      IF (ABS(AIMAG(ZI(I1))) .LE. EP3) GO TO 51
      GO TO 50
   51 J=J+1
      C(J)=REAL(ZI(I1))
   50 CONTINUE
C     SELECTED THE REAL ZERO
C
C     START TO SELECT THE CORRECT ZERO
      N=
      IF (J .EQ. 0) GO TO 160
      DO 60 J2=1,J
      IF (C(J2) .GE. 0. .AND. C(J2) .LE. RADIUS) GO TO 55
      GO TO 60
   55 N=N+1
      CI(N)=C(J2)
```

```
   60 CONTINUE
      K3=0
      IF (N-1) 160,65,165
C     TREAT MULTIPLE (DOUBLE) ROOTS AS ONE ROOT IF THEIR DIFFERENCE
C     IS WITHIN EP4
  165 J33=N-1
      K2=0
      DO 167 J3=1,J33
      IF (ABS(CI(J3)-CI(J3+1)) .LE. EP4) GO TO 166
C     TREAT MULTIPLE (DOUBLE) ROOTS AS SEPARATE ROOTS IF THEIR
C     DIFFERENCE IS NOT WITHIN EP4
      K3=K3+1
      CN(K3)=CI(J3)
      GO TO 167
  166 CM=CI(J3)
      K2=K2+1
  167 CONTINUE
      IF (K2-1) 206,66,66
   65 CM=CI(N)
C     SELECTED THE CORRECT ZERO
C
C     START DOUBLE CHECK
   66 DIS=(CM**2+2.*CM*AP+E)**0.5
      YY1=F+CM*B
      SS=S+U*YY1/DIS
      TIME=DIS/SS
      CTIME=SI/AM+TIME
      IF (ABS(T(I)-CTIME) .GE. EP5) GO TO 160
C     END OF DOUBLE CHECK
C
C     USE TWO DIFFERENT INCREMENT DS AND DSI
  205 IF (KO-1) 210,221,221
  210 SI=SI+DS-DSI
      KO=1
      GO TO 180
  206 IF (K3-1) 160,207,207
C     DOUBLE-CHECK MULTIPLE (DOUBLE) ROOTS WHOSE DIFFERENCE IS NOT
C     WITHIN EP4
  207 K6=0
      K33=K3-1
      DO 208 K5=1,K33
      DIS=(CN(K5)**2+2.*CN(K5)*AP+E)**0.5
      YY1=F+CN(K5)*B
      SS=S+U*YY1/DIS
      TIME=DIS/SS
```

```
      CTIME=SI/AM+TIME
      IF (ABS(T(I)-CTIME) .GE. EPS) GO TO 208
      K6=K6+1
      CP(K6)=CN(K5)
  208 CONTINUE
      IF (K6-1) 160,222,222
  222 IF (K0-1) 210,226,226
  226 WRITE (6,22) K6
      DO 223 K4=1,K6
      K=K+1
      R(I,K)=CN(K4)
      ANG(I,K)=SI
      DEG=180.*SI/3.1416
  223 WRITE (6,12) R(I,K),ANG(I,K),DEG,I,K,DIS,TIME,CTIME
      WRITE (6,23)
      GO TO 224
  221 K=K+1
      R(I,K)=CM
      ANG(I,K)=SI
C     OBTAINED THE CORRECT R AND SI
      DEG=180.*SI/3.1416
      WRITE (6,12) R(I,K),ANG(I,K),DEG,I,K,DIS,TIME,CTIME
  224 K1=0
      K0=2
  230 SI=SI-DSI
      GO TO 180
  160 IF (K0-1) 190,230,240
  240 K1=K1+1
      IF (K1-KIN) 230,230,250
  250 K0=0
  190 SI=SI-DS
  180 IF (SI .GE. SIF) GO TO 150
      KA(I)=K
      WRITE (6,18)
   10 CONTINUE
C     END OF ALL N MICROPHONES CALCULATION
C
C     IF COMPARISONS ARE NEEDED, THE DECK SHOULD BE INSERTED HERE.
  290 STOP
      END
```

APPENDIX 2

```
T437 RUN 28.2
 34.245     0.        0.        70.       247.09              6
 68.24      6.99      68.58     -13.84    68.85     12.41
 -20.       5.        0.        10.92      20.      12.83
  8.06      1.25      8.07      -1.08     8.08       7.
 .1390      .0565     .1300     .0235     .1255     .0610
 0.0349     0.0175    1.00      0.0360
  1.        .5        .001                3
  6.2832    -3.1416
  6.94       .0349
 24.
```

```
R= 23.9   ANG=  2.1300  =  122.04DEG   I= 3   K= 1   DIS= 61.5   TIME=  .0670   CTIME=  .1300
R= 23.7   ANG=  2.1125  =  121.04DEG   I= 3   K= 2   DIS= 62.0   TIME=  .0665   CTIME=  .1300
R= 23.4   ANG=  2.0950  =  120.03DEG   I= 3   K= 3   DIS= 62.4   TIME=  .0688   CTIME=  .1300
R= 23.1   ANG=  2.0775  =  119.03DEG   I= 3   K= 4   DIS= 62.8   TIME=  .0693   CTIME=  .1300
R= 22.8   ANG=  2.0600  =  118.03DEG   I= 3   K= 5   DIS= 63.3   TIME=  .0698   CTIME=  .1300
R= 22.4   ANG=  2.0425  =  117.03DEG   I= 3   K= 6   DIS= 63.7   TIME=  .0704   CTIME=  .1300
R= 22.0   ANG=  2.0250  =  116.02DEG   I= 3   K= 7   DIS= 64.1   TIME=  .0709   CTIME=  .1300
R= 21.5   ANG=  2.0075  =  115.02DEG   I= 3   K= 8   DIS= 64.5   TIME=  .0714   CTIME=  .1300
R= 21.0   ANG=  1.9900  =  114.02DEG   I= 3   K= 9   DIS= 65.0   TIME=  .0719   CTIME=  .1300
R= 20.4   ANG=  1.9725  =  113.02DEG   I= 3   K=10   DIS= 65.4   TIME=  .0724   CTIME=  .1300
R= 19.7   ANG=  1.9550  =  112.01DEG   I= 3   K=11   DIS= 65.8   TIME=  .0729   CTIME=  .1300
R= 18.8   ANG=  1.9375  =  111.01DEG   I= 3   K=12   DIS= 66.2   TIME=  .0734   CTIME=  .1300
R= 17.9   ANG=  1.9200  =  110.01DEG   I= 3   K=13   DIS= 66.5   TIME=  .0739   CTIME=  .1300
R= 16.8   ANG=  1.9025  =  109.00DEG   I= 3   K=14   DIS= 66.9   TIME=  .0744   CTIME=  .1300
R= 15.5   ANG=  1.8850  =  108.00DEG   I= 3   K=15   DIS= 67.3   TIME=  .0750   CTIME=  .1300
R= 14.0   ANG=  1.8675  =  107.00DEG   I= 3   K=16   DIS= 67.7   TIME=  .0755   CTIME=  .1300
R= 12.4   ANG=  1.8500  =  106.00DEG   I= 3   K=17   DIS= 68.0   TIME=  .0760   CTIME=  .1300
R= 10.6   ANG=  1.8325  =  104.99DEG   I= 3   K=18   DIS= 68.4   TIME=  .0765   CTIME=  .1300
R=  8.5   ANG=  1.8150  =  103.99DEG   I= 3   K=19   DIS= 68.8   TIME=  .0770   CTIME=  .1300
R=  6.3   ANG=  1.7975  =  102.99DEG   I= 3   K=20   DIS= 69.1   TIME=  .0775   CTIME=  .1300
R=  4.0   ANG=  1.7800  =  101.99DEG   I= 3   K=21   DIS= 69.5   TIME=  .0780   CTIME=  .1300
R=  1.5   ANG=  1.7625  =  100.98DEG   I= 3   K=22   DIS= 70.0   TIME=  .0785   CTIME=  .1300
END OF I-PRINT


 1  ROOTS
R= 18.3   ANG=   .5944  =   34.06DEG   I= 4   K= 1   DIS=  6.7   TIME=  .0061   CTIME=  .0235
END OF MULTIPLE ROOTS

 1  ROOTS
R= 19.4   ANG=   .5769  =   33.05DEG   I= 4   K= 2   DIS=  7.0   TIME=  .0067   CTIME=  .0235
END OF MULTIPLE ROOTS

 1  ROOTS
R= 20.2   ANG=   .5594  =   32.05DEG   I= 4   K= 3   DIS=  7.3   TIME=  .0072   CTIME=  .0235
END OF MULTIPLE ROOTS
```

APPENDIX 3

REPRODUCIBILITY OF THE ORIGINAL PAGE IS POOR

```
T437 RUN 28.2
RADIUS=   24.0000
G= 6.94FT AM=  34.2430RAD/SEC AS=  0.0000RAD AT=  0.0000RAD AZ=   .0349RAD  TEM=   70.00F
X=    68.24     6.99    68.58   -13.84    68.83    12.41                 L=  247.19FPS   n  1[illegible]
Y=   -20.00     5.00     0.00    10.92    20.00    12.83
Z=     8.06     1.25     8.07    -1.08     8.08     7.06
T=    .1390    .0565    .1300    .0235    .1255    .0610
SII=    6.2832  SIF=   -3.1416
DS=  .0349RAD  DSI=  .0175RAD  EP1= 1.0000FT  EP2=  .0360RAD
EP3=   1.0000  EP4=     .5000  EP5=     .0010  KIN=    5

R= 23.8  ANG=  2.4616  =  141.04DEG  I= 1  K= 1   DIS= 62.8  TIME=  .0671  CTIME=  .1390
R= 23.5  ANG=  2.4441  =  140.04DEG  I= 1  K= 2   DIS= 63.3  TIME=  .0676  CTIME=  .1390
R= 23.2  ANG=  2.4266  =  139.03DEG  I= 1  K= 3   DIS= 63.7  TIME=  .0681  CTIME=  .1390
R= 22.9  ANG=  2.4091  =  138.03DEG  I= 1  K= 4   DIS= 64.2  TIME=  .0686  CTIME=  .1390
R= 22.6  ANG=  2.3916  =  137.03DEG  I= 1  K= 5   DIS= 64.6  TIME=  .0692  CTIME=  .1390
R= 22.3  ANG=  2.3741  =  136.03DEG  I= 1  K= 6   DIS= 65.1  TIME=  .0697  CTIME=  .1390
R= 22.0  ANG=  2.3566  =  135.02DEG  I= 1  K= 7   DIS= 65.5  TIME=  .0702  CTIME=  .1390
R= 21.6  ANG=  2.3391  =  134.02DEG  I= 1  K= 8   DIS= 65.9  TIME=  .0707  CTIME=  .1390
R= 21.2  ANG=  2.3216  =  133.02DEG  I= 1  K= 9   DIS= 66.3  TIME=  .0712  CTIME=  .1390
R= 20.8  ANG=  2.3041  =  132.01DEG  I= 1  K=10   DIS= 66.8  TIME=  .0717  CTIME=  .1390
R= 20.3  ANG=  2.2866  =  131.01DEG  I= 1  K=11   DIS= 67.2  TIME=  .0722  CTIME=  .1390
R= 19.8  ANG=  2.2691  =  130.01DEG  I= 1  K=12   DIS= 67.6  TIME=  .0727  CTIME=  .1390
R= 19.2  ANG=  2.2516  =  129.01DEG  I= 1  K=13   DIS= 68.0  TIME=  .0732  CTIME=  .1390
R= 18.6  ANG=  2.2341  =  128.00DEG  I= 1  K=14   DIS= 68.3  TIME=  .0738  CTIME=  .1390
R= 17.9  ANG=  2.2166  =  127.00DEG  I= 1  K=15   DIS= 68.7  TIME=  .0743  CTIME=  .1390
R= 17.1  ANG=  2.1991  =  126.00DEG  I= 1  K=16   DIS= 69.1  TIME=  .0748  CTIME=  .1390
R= 16.3  ANG=  2.1816  =  125.00DEG  I= 1  K=17   DIS= 69.5  TIME=  .0753  CTIME=  .1390
R= 15.3  ANG=  2.1641  =  123.99DEG  I= 1  K=18   DIS= 69.8  TIME=  .0758  CTIME=  .1390
R= 14.3  ANG=  2.1466  =  122.99DEG  I= 1  K=19   DIS= 70.1  TIME=  .0763  CTIME=  .1390
R= 13.1  ANG=  2.1291  =  121.99DEG  I= 1  K=20   DIS= 70.5  TIME=  .0768  CTIME=  .1390
R= 11.9  ANG=  2.1116  =  120.99DEG  I= 1  K=21   DIS= 70.8  TIME=  .0773  CTIME=  .1390
R= 10.5  ANG=  2.0941  =  119.98DEG  I= 1  K=22   DIS= 71.1  TIME=  .0778  CTIME=  .1390
R=  8.9  ANG=  2.0766  =  118.98DEG  I= 1  K=23   DIS= 71.4  TIME=  .0784  CTIME=  .1390
R=  7.3  ANG=  2.0591  =  117.98DEG  I= 1  K=24   DIS= 71.6  TIME=  .0789  CTIME=  .1390
R=  5.5  ANG=  2.0416  =  116.97DEG  I= 1  K=25   DIS= 71.9  TIME=  .0794  CTIME=  .1390
R=  3.5  ANG=  2.0241  =  115.97DEG  I= 1  K=26   DIS= 72.2  TIME=  .0799  CTIME=  .1390
R=  1.5  ANG=  2.0066  =  114.97DEG  I= 1  K=27   DIS= 72.5  TIME=  .0804  CTIME=  .1390
END OF I-PRINT
```

```
 1  ROOTS
R=  7.2   ANG=  1.5367  =   88.05DEG   I= 2   K= 1   DIS= 11.3   TIME=   .0116   CTIME=   .0565
END OF MULTIPLE ROOTS

R=  8.6   ANG=  1.5192  =   87.04DEG   I= 2   K= 2   DIS= 11.9   TIME=   .0121   CTIME=   .0565
R=  9.7   ANG=  1.5017  =   86.04DEG   I= 2   K= 3   DIS= 12.4   TIME=   .0126   CTIME=   .0565
R= 10.6   ANG=  1.4842  =   85.04DEG   I= 2   K= 4   DIS= 12.9   TIME=   .0132   CTIME=   .0565
R= 11.4   ANG=  1.4667  =   84.04DEG   I= 2   K= 5   DIS= 13.4   TIME=   .0137   CTIME=   .0565
R= 12.0   ANG=  1.4492  =   83.03DEG   I= 2   K= 6   DIS= 13.9   TIME=   .0142   CTIME=   .0565
R= 12.7   ANG=  1.4317  =   82.03DEG   I= 2   K= 7   DIS= 14.4   TIME=   .0147   CTIME=   .0565
R= 13.3   ANG=  1.4142  =   81.03DEG   I= 2   K= 8   DIS= 14.9   TIME=   .0152   CTIME=   .0565
R= 13.9   ANG=  1.3967  =   80.02DEG   I= 2   K= 9   DIS= 15.4   TIME=   .0157   CTIME=   .0565
R= 14.4   ANG=  1.3792  =   79.02DEG   I= 2   K=10   DIS= 15.9   TIME=   .0162   CTIME=   .0565
R= 14.9   ANG=  1.3617  =   78.02DEG   I= 2   K=11   DIS= 16.4   TIME=   .0167   CTIME=   .0565
R= 15.4   ANG=  1.3442  =   77.02DEG   I= 2   K=12   DIS= 16.9   TIME=   .0172   CTIME=   .0565
R= 15.9   ANG=  1.3267  =   76.01DEG   I= 2   K=13   DIS= 17.4   TIME=   .0178   CTIME=   .0565
R= 16.3   ANG=  1.3092  =   75.01DEG   I= 2   K=14   DIS= 17.8   TIME=   .0183   CTIME=   .0565
R= 16.8   ANG=  1.2917  =   74.01DEG   I= 2   K=15   DIS= 18.3   TIME=   .0188   CTIME=   .0565
R= 17.2   ANG=  1.2742  =   73.01DEG   I= 2   K=16   DIS= 18.8   TIME=   .0193   CTIME=   .0565
R= 17.6   ANG=  1.2567  =   72.00DEG   I= 2   K=17   DIS= 19.3   TIME=   .0198   CTIME=   .0565
R= 18.1   ANG=  1.2392  =   71.00DEG   I= 2   K=18   DIS= 19.7   TIME=   .0203   CTIME=   .0565
R= 18.5   ANG=  1.2217  =   70.00DEG   I= 2   K=19   DIS= 20.2   TIME=   .0208   CTIME=   .0565
R= 18.9   ANG=  1.2042  =   69.00DEG   I= 2   K=20   DIS= 20.6   TIME=   .0213   CTIME=   .0565
R= 19.3   ANG=  1.1867  =   67.99DEG   I= 2   K=21   DIS= 21.1   TIME=   .0218   CTIME=   .0565
R= 19.6   ANG=  1.1692  =   66.99DEG   I= 2   K=22   DIS= 21.5   TIME=   .0224   CTIME=   .0565
R= 20.0   ANG=  1.1517  =   65.99DEG   I= 2   K=23   DIS= 22.0   TIME=   .0229   CTIME=   .0565
R= 20.4   ANG=  1.1342  =   64.98DEG   I= 2   K=24   DIS= 22.4   TIME=   .0234   CTIME=   .0565
R= 20.8   ANG=  1.1167  =   63.98DEG   I= 2   K=25   DIS= 22.9   TIME=   .0239   CTIME=   .0565
R= 21.1   ANG=  1.0992  =   62.98DEG   I= 2   K=26   DIS= 23.3   TIME=   .0244   CTIME=   .0565
R= 21.5   ANG=  1.0817  =   61.98DEG   I= 2   K=27   DIS= 23.8   TIME=   .0249   CTIME=   .0565
R= 21.8   ANG=  1.0642  =   60.97DEG   I= 2   K=28   DIS= 24.2   TIME=   .0254   CTIME=   .0565
R= 22.2   ANG=  1.0467  =   59.97DEG   I= 2   K=29   DIS= 24.7   TIME=   .0259   CTIME=   .0565
R= 22.5   ANG=  1.0292  =   58.97DEG   I= 2   K=30   DIS= 25.1   TIME=   .0264   CTIME=   .0565
R= 22.8   ANG=  1.0117  =   57.97DEG   I= 2   K=31   DIS= 25.5   TIME=   .0270   CTIME=   .0565
R= 23.2   ANG=   .9942  =   56.96DEG   I= 2   K=32   DIS= 26.0   TIME=   .0275   CTIME=   .0565
R= 23.5   ANG=   .9767  =   55.96DEG   I= 2   K=33   DIS= 26.4   TIME=   .0280   CTIME=   .0565
R= 23.8   ANG=   .9592  =   54.96DEG   I= 2   K=34   DIS= 26.8   TIME=   .0285   CTIME=   .0565
END OF I-PRINT
```

```
 1  ROOTS
R= 20.8   ANG=  .5419  =  31.05DEG  I= 4  K= 4  DIS=  7.7  TIME=  .0077  CTIME=  .0235
END OF MULTIPLE ROOTS

 1  ROOTS
R= 21.4   ANG=  .5244  =  30.05DEG  I= 4  K= 5  DIS=  8.1  TIME=  .0082  CTIME=  .0235
END OF MULTIPLE ROOTS

 1  ROOTS
R= 21.9   ANG=  .5069  =  29.04DEG  I= 4  K= 6  DIS=  8.5  TIME=  .0087  CTIME=  .0235
END OF MULTIPLE ROOTS

 1  ROOTS
R= 22.4   ANG=  .4894  =  28.04DEG  I= 4  K= 7  DIS=  8.9  TIME=  .0092  CTIME=  .0235
END OF MULTIPLE ROOTS

 1  ROOTS
R= 22.9   ANG=  .4719  =  27.04DEG  I= 4  K= 8  DIS=  9.3  TIME=  .0097  CTIME=  .0235
END OF MULTIPLE ROOTS

 1  ROOTS
R= 23.3   ANG=  .4544  =  26.04DEG  I= 4  K= 9  DIS=  9.7  TIME=  .0102  CTIME=  .0235
END OF MULTIPLE ROOTS

 1  ROOTS
R= 23.7   ANG=  .4369  =  25.03DEG  I= 4  K=10  DIS= 10.2  TIME=  .0107  CTIME=  .0235
END OF MULTIPLE ROOTS

R=  4.5   ANG=  .4194  =  24.03DEG  I= 4  K=11  DIS= 14.6  TIME=  .0113  CTIME=  .0235
R=  3.7   ANG=  .4019  =  23.03DEG  I= 4  K=12  DIS= 15.3  TIME=  .0118  CTIME=  .0235
R=  2.9   ANG=  .3844  =  22.02DEG  I= 4  K=13  DIS= 16.0  TIME=  .0123  CTIME=  .0235
R=  2.1   ANG=  .3669  =  21.02DEG  I= 4  K=14  DIS= 16.7  TIME=  .0126  CTIME=  .0235
R=  1.3   ANG=  .3494  =  20.02DEG  I= 4  K=15  DIS= 17.4  TIME=  .0133  CTIME=  .0235
R=   .5   ANG=  .3319  =  19.02DEG  I= 4  K=16  DIS= 18.1  TIME=  .0136  CTIME=  .0235
END OF I-PRINT
```

```
R= 23.9   ANG= 1.6763  =  96.04DEG  I= 5  K= 1   DIS= 68.5  TIME= .0765  CTIME= .1255
R= 23.0   ANG= 1.6588  =  95.04DEG  I= 5  K= 2   DIS= 68.7  TIME= .0771  CTIME= .1255
R= 21.5   ANG= 1.6413  =  94.04DEG  I= 5  K= 3   DIS= 69.2  TIME= .0776  CTIME= .1255
R= 19.5   ANG= 1.6238  =  93.04DEG  I= 5  K= 4   DIS= 69.6  TIME= .0781  CTIME= .1255
R= 17.0   ANG= 1.6063  =  92.03DEG  I= 5  K= 5   DIS= 70.1  TIME= .0786  CTIME= .1255
R= 14.2   ANG= 1.5888  =  91.03DEG  I= 5  K= 6   DIS= 70.5  TIME= .0791  CTIME= .1255
R= 11.2   ANG= 1.5713  =  90.03DEG  I= 5  K= 7   DIS= 71.1  TIME= .0796  CTIME= .1255
R=  8.1   ANG= 1.5538  =  89.03DEG  I= 5  K= 8   DIS= 71.6  TIME= .0801  CTIME= .1255
R=  4.8   ANG= 1.5363  =  88.02DEG  I= 5  K= 9   DIS= 72.3  TIME= .0806  CTIME= .1255
R=  1.6   ANG= 1.5188  =  87.02DEG  I= 5  K=10   DIS= 72.9  TIME= .0811  CTIME= .1255
END OF I-PRINT

 1  ROOTS
R= 10.9   ANG= 1.3448  =  77.05DEG  I= 6  K= 1   DIS= 20.8  TIME= .0217  CTIME= .0610
END OF MULTIPLE ROOTS

 1  ROOTS
R= 12.8   ANG= 1.3273  =  76.05DEG  I= 6  K= 2   DIS= 21.1  TIME= .0222  CTIME= .0610
END OF MULTIPLE ROOTS

R= 14.0   ANG= 1.3098  =  75.05DEG  I= 6  K= 3   DIS= 21.6  TIME= .0227  CTIME= .0610
R= 15.0   ANG= 1.2923  =  74.04DEG  I= 6  K= 4   DIS= 22.0  TIME= .0233  CTIME= .0610
R= 15.8   ANG= 1.2746  =  73.04DEG  I= 6  K= 5   DIS= 22.5  TIME= .0238  CTIME= .0610
R= 16.5   ANG= 1.2573  =  72.04DEG  I= 6  K= 6   DIS= 22.9  TIME= .0243  CTIME= .0610
R= 17.1   ANG= 1.2398  =  71.04DEG  I= 6  K= 7   DIS= 23.4  TIME= .0248  CTIME= .0610
R= 17.7   ANG= 1.2223  =  70.03DEG  I= 6  K= 8   DIS= 23.8  TIME= .0253  CTIME= .0610
R= 18.2   ANG= 1.2048  =  69.03DEG  I= 6  K= 9   DIS= 24.2  TIME= .0258  CTIME= .0610
R= 18.7   ANG= 1.1873  =  68.03DEG  I= 6  K=10   DIS= 24.7  TIME= .0263  CTIME= .0610
R= 19.2   ANG= 1.1698  =  67.02DEG  I= 6  K=11   DIS= 25.1  TIME= .0268  CTIME= .0610
R= 19.6   ANG= 1.1523  =  66.02DEG  I= 6  K=12   DIS= 25.6  TIME= .0273  CTIME= .0610
R= 20.0   ANG= 1.1348  =  65.02DEG  I= 6  K=13   DIS= 26.0  TIME= .0279  CTIME= .0610
R= 20.4   ANG= 1.1173  =  64.02DEG  I= 6  K=14   DIS= 26.5  TIME= .0284  CTIME= .0610
R= 20.8   ANG= 1.0998  =  63.01DEG  I= 6  K=15   DIS= 26.9  TIME= .0289  CTIME= .0610
R= 21.1   ANG= 1.0823  =  62.01DEG  I= 6  K=16   DIS= 27.3  TIME= .0294  CTIME= .0610
R= 21.5   ANG= 1.0646  =  61.01DEG  I= 6  K=17   DIS= 27.8  TIME= .0299  CTIME= .0610
R= 21.8   ANG= 1.0473  =  60.01DEG  I= 6  K=18   DIS= 28.2  TIME= .0304  CTIME= .0610
R= 22.2   ANG= 1.0298  =  59.00DEG  I= 6  K=19   DIS= 28.7  TIME= .0309  CTIME= .0610
R= 22.5   ANG= 1.0123  =  58.00DEG  I= 6  K=20   DIS= 29.1  TIME= .0314  CTIME= .0610
R= 22.8   ANG=  .9948  =  57.00DEG  I= 6  K=21   DIS= 29.5  TIME= .0319  CTIME= .0610
R= 23.1   ANG=  .9773  =  56.00DEG  I= 6  K=22   DIS= 30.0  TIME= .0325  CTIME= .0610
R= 23.4   ANG=  .9598  =  54.99DEG  I= 6  K=23   DIS= 30.4  TIME= .0330  CTIME= .0610
R= 23.7   ANG=  .9423  =  53.99DEG  I= 6  K=24   DIS= 30.8  TIME= .0335  CTIME= .0610
R= 24.0   ANG=  .9248  =  52.99DEG  I= 6  K=25   DIS= 31.3  TIME= .0340  CTIME= .0610
END OF I-PRINT
```

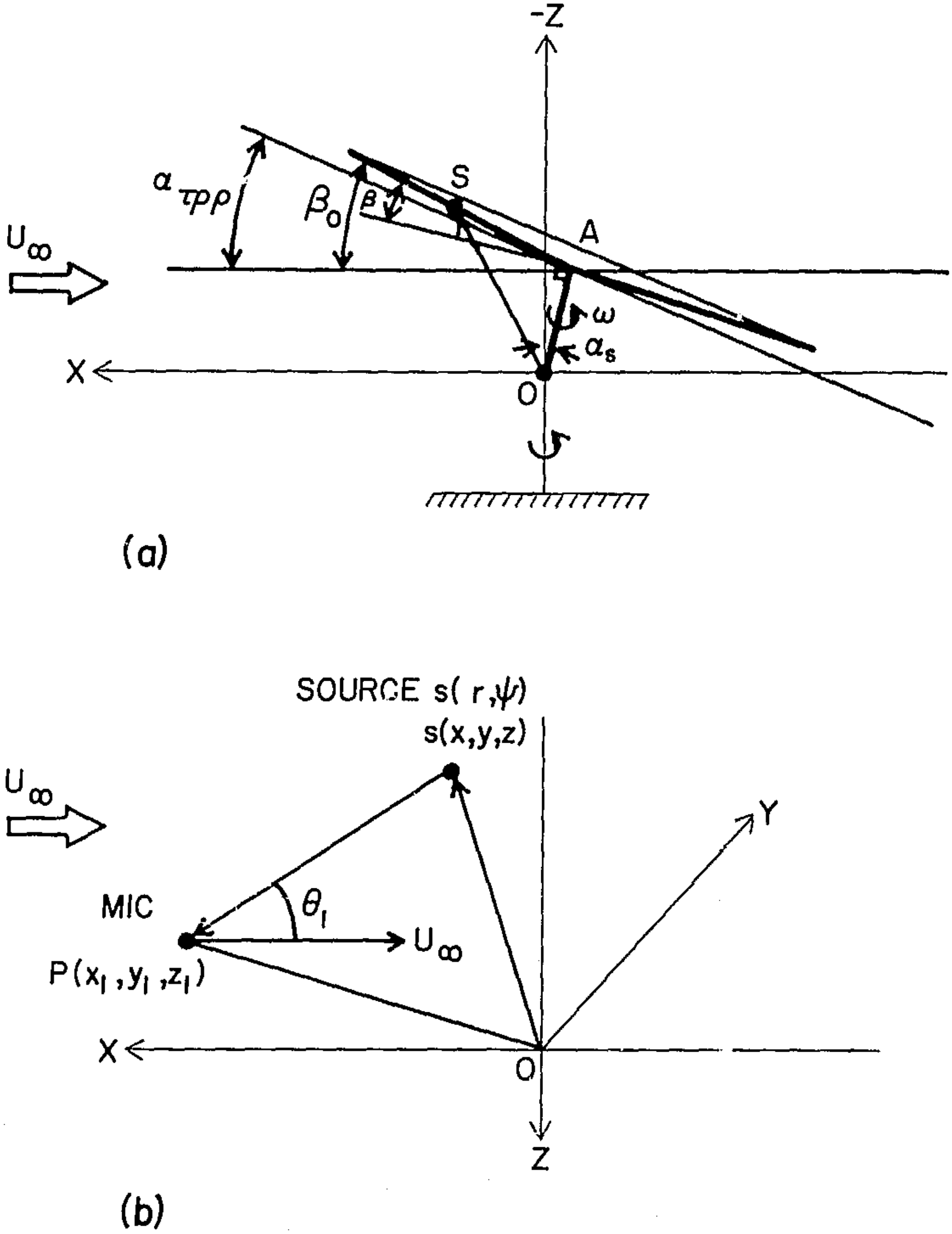

FIGURE 1.- DEFINITION OF COORDINATES

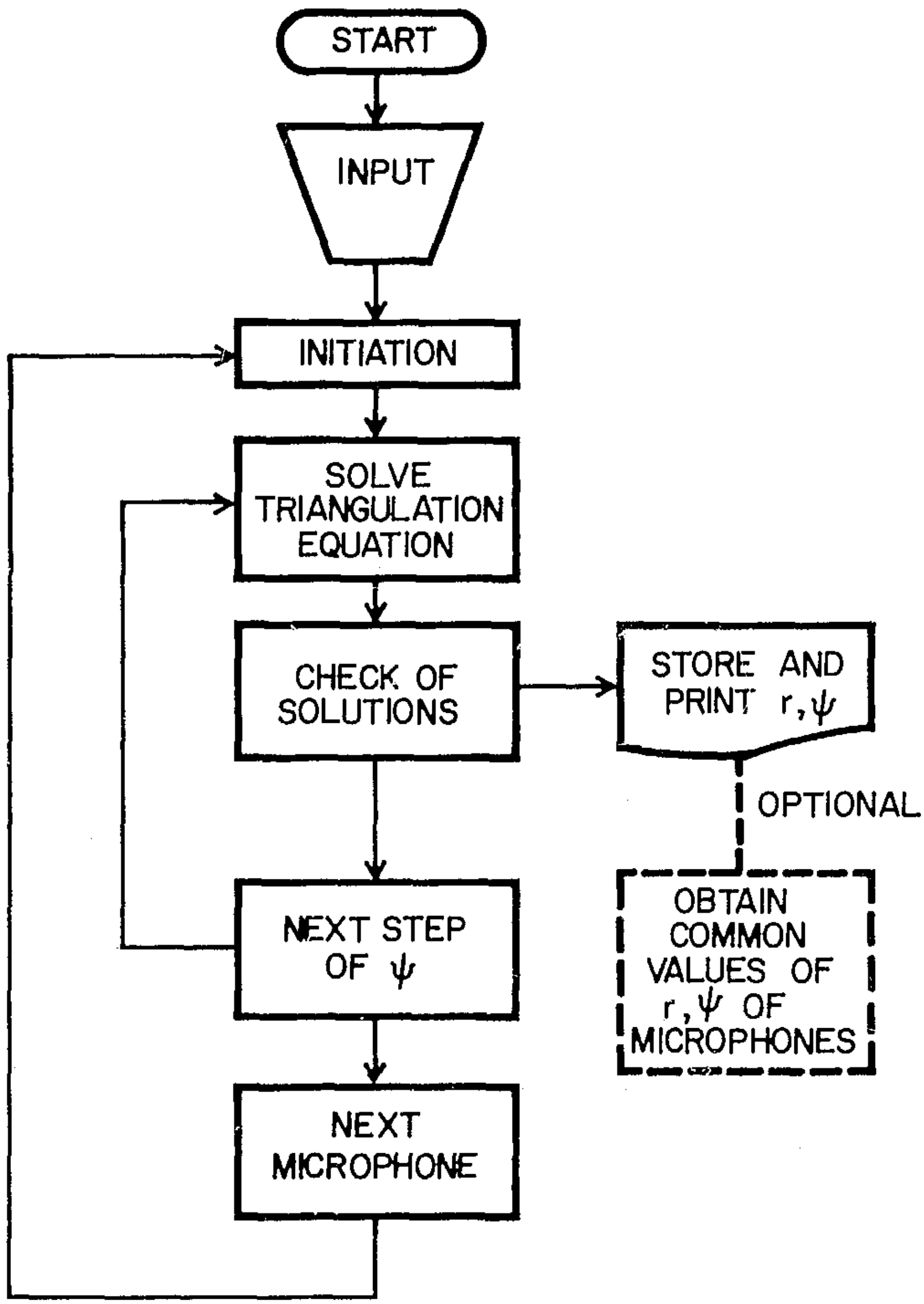

FIGURE 2.- BLOCK DIAGRAM

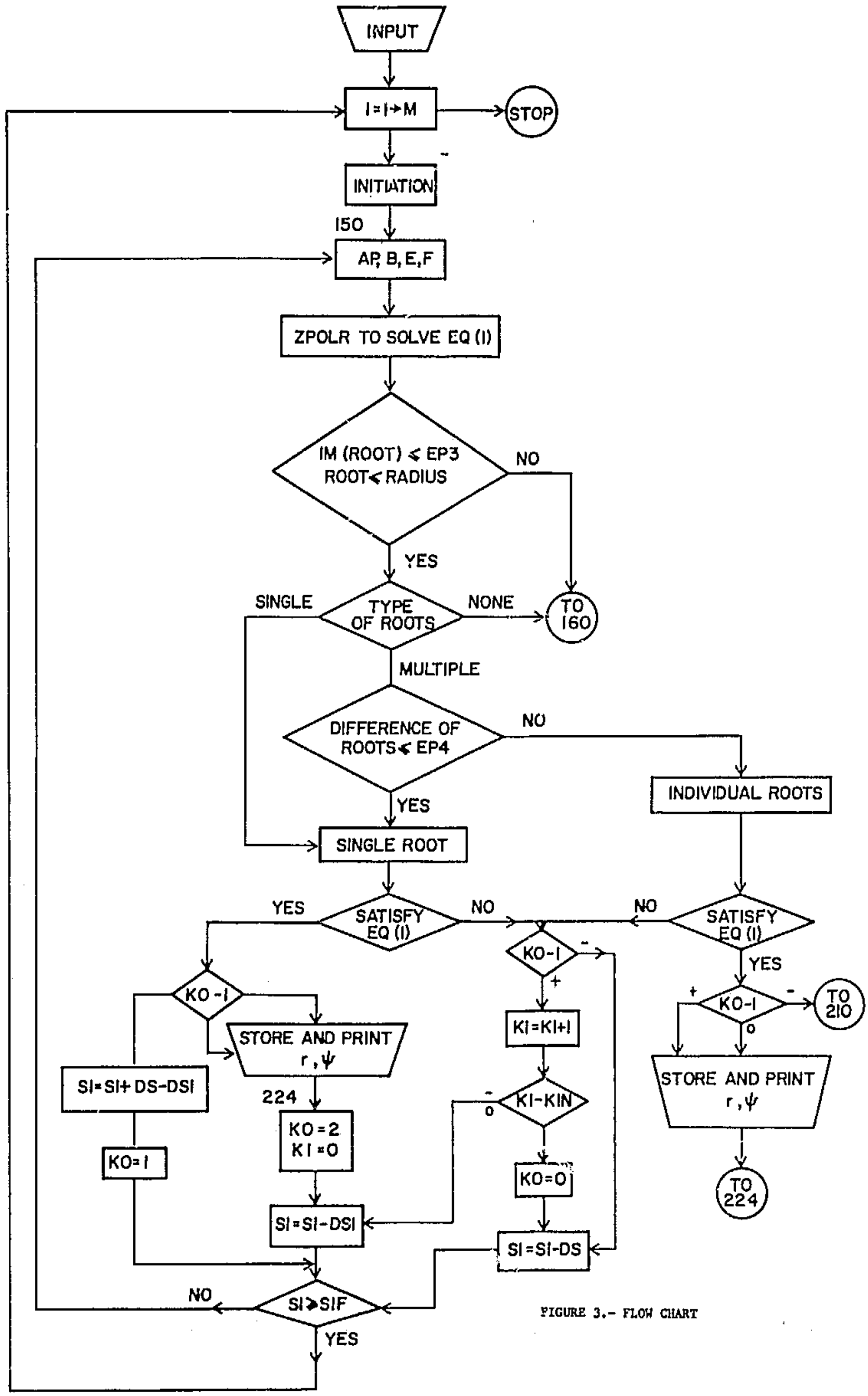

FIGURE 3.- FLOW CHART

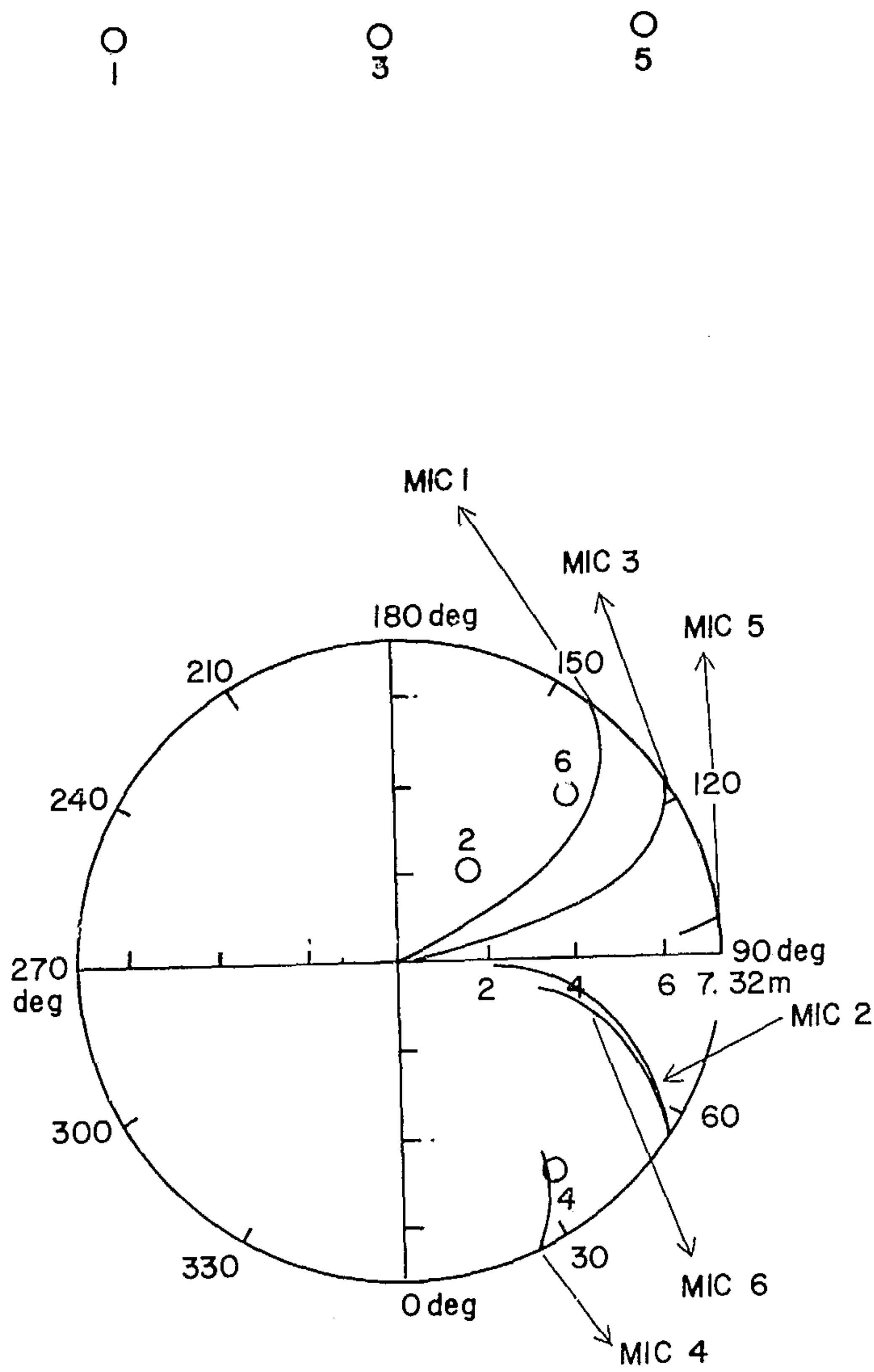

FIGURE 4.- RESULTS OF ACOUSTICAL TRIANGULATION