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A DIGITAL SIMULATION OF THE WULLENWEBER DIRECTION FINDING SYSTEM

(A final report on NOBSR 89229. The work
will be continued on NONR 1834(02))

by

EDWIN C. JONES, Jr.

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Technical Report No. 17
Contract NOBSR 89229

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Supported by
BUREAU OF SHIPS

RADIOLOCATION RESEARCH LABORATORY
DEPARTMENT OF ELECTRICAL ENGINEERING
ENGINEERING EXPERIMENT STATION
UNIVERSITY OF ILLINOIS
URBANA, ILLINOIS

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A DIGITAL SIMULATION OF THE WULLENWEBER DIRECTION FINDING SYSTEM

The purpose of this report is to describe the development of a digital model for simulation of the University of Illinois Wullenweber direction finding system when operating in the scanning mode. Such a study has been motivated by two considerations. The first is the desire to study the accuracy and sensitivity problems in the present system, and to explore questions of performance degradation when certain engineering specifications are relaxed. The second is to have at the disposal of the Radiolocation Research Laboratory a "tool" which might be used to study ideas for future system development and improvement. Such studies would logically precede the construction of any new systems, or extensive modifications of the present system. Actual uses of the resulting digital simulation model will be subjects for later reports and/or notes.

The University of Illinois Wullenweber array is located near Bondville, Illinois. It is a circular array of 120 vertical monopoles located on the periphery of a circle about 303 meters (994 feet) in diameter. Antenna No. 1 is located on an azimuth of 3° from true north, antenna No. 2 is located on an azimuth of 6°, and so on. Behind the antenna array is a circular reflector, 291.0 meters in diameter, and about 20 meters high. The distance between the reflector and the antenna elements is 5.94 meters.

At the base of each antenna is a transformer. This is used to match the impedance levels of the antennas and the cables.

From the transformers buried coaxial cables lead to the equipment building at the center of the array. These are Styroflex 50 ohm cables, with a spiral dielectric of a laminated plastic, and operate under pressure.

When purchased, the velocities of propagation of signals in the cables were to be within 1% of the central value of the set of cables. The cables were individually cut to length by insuring that each was 13.50 wavelengths long at 10.45 megahertz.

At the terminal, each cable (and thus antenna output) is connected to a "multicoupler", which is an amplifier having one input and four isolated outputs.

One set of 120 outputs is connected to the "LOW-BAND" antenna scanner (commonly called a goniometer), a second set to the "HIGH-BAND" antenna scanner, and the third and fourth sets are free for other experiments.

This scanner is an electromechanical signal processor, and it combines a prescribed portion of the 120 antenna signals in a way that makes the circular array represent a rotating linear array. In this report, the "LOW-BAND" will be considered; the "HIGH-BAND" is quite similar except for the number of elements.

The function of the scanner is to select 48 antennas, centered on the "boresight", or the instantaneous direction of the reference axis of the scanner, and to combine the signals from these antennas. This is done in several steps.

The first step involves the 24 antennas on one side of the boresight. Consider the drawing of Fig. 1, which shows an incoming signal whose wavefront is perpendicular to a vertical plane containing the boresight.

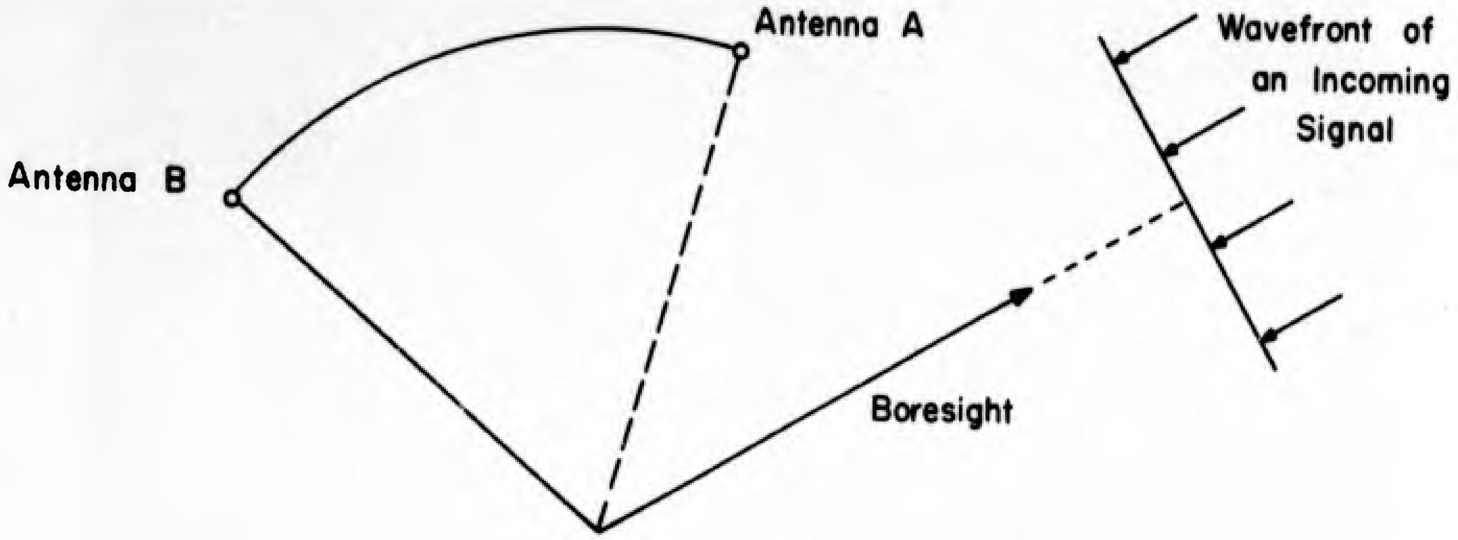


Figure 1. Illustration of Delay in Circular Array

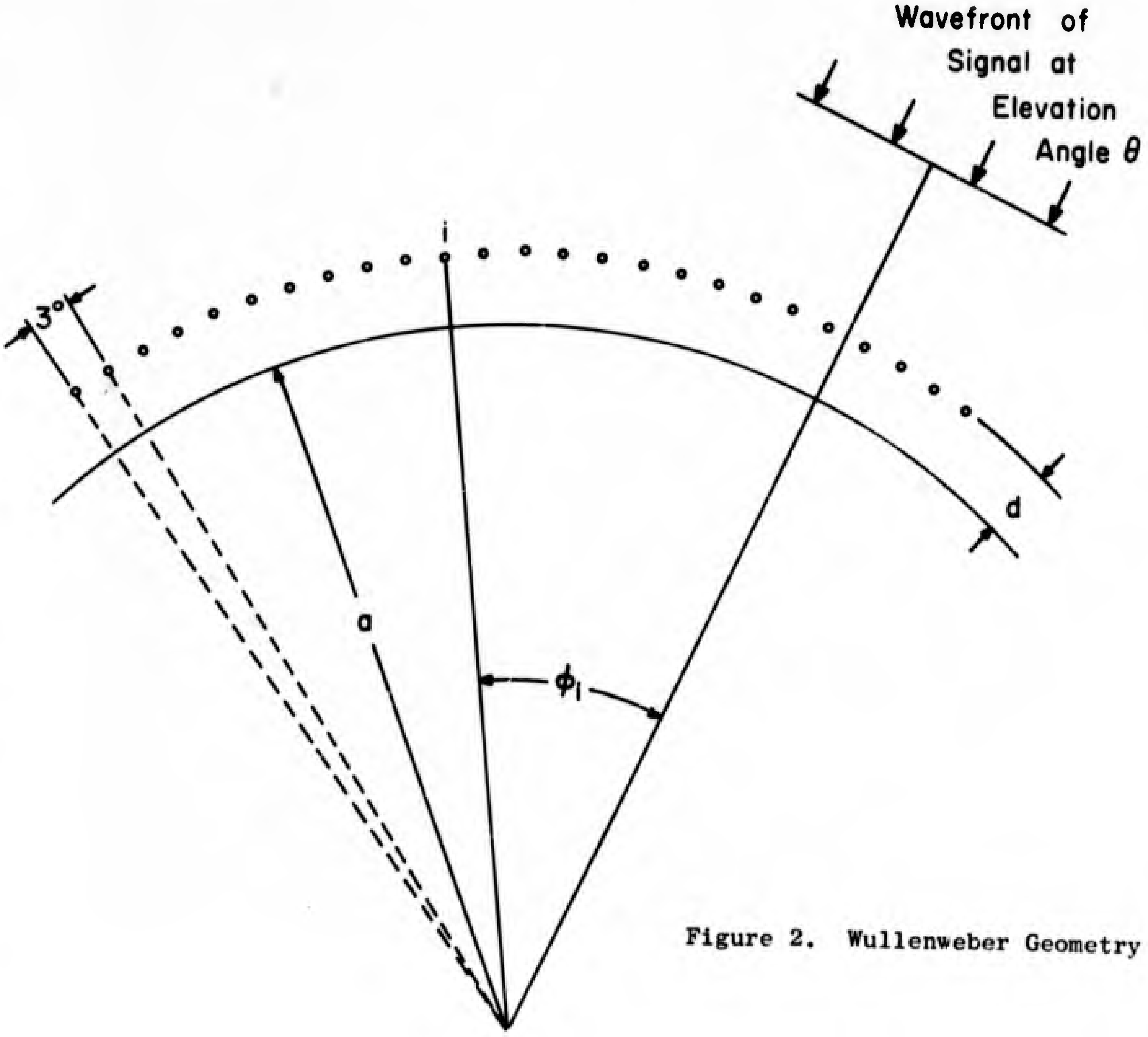


Figure 2. Wullenweber Geometry

The phase of the signal at Antenna B will be delayed compared with that at A. But if the array were linear, this would not be true. Consequently, the signal on Antenna A must be delayed so that when it is compared with the signal on B, the two signals will be in phase. In practice, the LOW-BAND scanner considers two sets of 24 antennas, one set on each side of the boresight, delays the various signals by appropriate amounts, and adds them. The result is two voltages, one representing the "left-side" of the scanner, one the "right-side".

The required amount of delay will vary with the elevation angle (above the horizon) of the incoming signal. Since variable delays are not practical, the delays must be set for a particular elevation angle. In this case the angle is 20°. This is called the "cophasal angle."

The "HIGH-BAND" scanner selects 24 antennas, 12 on each side, and uses a cophasal angle of 10°.

The outputs of the two halves of the goniometer are then combined in a hybrid transformer, so that both the sum of and difference between these two signals are available for further processing.

The remainder of the system includes a receiver and a rotating display. The receiver is an AM receiver, and the output is applied to the deflection system of a cathode ray tube - the deflection yoke is rotating at the same speed and relative position as the scanner, so that the deflection is then an indication of the signal energy reaching the array from a specific direction.

The Digital Model

A complete digital model of this rather complex system would include transfer functions for all components, and also equations for the interactions when appropriate. But, certain parts of any system have lesser effects than others, and can effectively be disregarded, which means that they are assumed to be ideal. If desired, they can be considered in future analyses.

In this system, the transformers and multicouplers have been considered ideal. Also, the receiver and display have been assumed linear, which is to say that the analyses will be concerned with the antenna scanner output voltages, and that no terms representing the receiver and display will be used.

The equations for the elementary patterns of the individual antenna elements have been published in an earlier report from this laboratory(1). In turn, these were derived from the work of Carter(2). The amplitude pattern is given by

$$A_i\ (r, \phi, \theta) = \cos\theta\ [\sin(\frac{2\pi d}{\lambda} \cdot \cos\phi\ \cos\theta)],$$

and the phase pattern by

$$P_i\ (r, \phi, \theta) = \frac{2\pi a}{\lambda} \cdot \cos\phi\ \cos\theta,$$

where λ = wavelength of incoming signal

d = antenna-screen spacing

a = radius of reflecting cylinder

ϕ = azimuthal angle for the element

θ = elevation angle for the element

Figure 2 shows the geometry.

The design of the antennas is such that the effects of coupling between elements may be neglected.

The model that has been programmed uses as input data the azimuth, elevation angle, and frequency (in megahertz) of an assumed incoming signal, and from this determines the amplitude and phase responses of the sixty (60) antennas illuminated by that particular signal. The remaining sixty (60) responses are set to zero.

The effects of the cables are to attenuate the signal and to shift its phase. Their computer representation includes both possibilities. The required input data are attenuation constant in nepers per meter, cable length in meters, and velocity of signal propagation expressed as a decimal fraction of the free space velocity.

The digital model for the antenna scanners is complex in the sense that many operations are necessary in its execution. It is required to simulate the continuous processing of signals by the scanner by a discrete set of numbers. The scanner input data will be the speed of rotation in revolutions per minute, the time of operation to be simulated in seconds, and the number of samples being taken every revolution. Because the effective beamwidth of the system is of the order of ten degrees (10^{o}), it is wasteful of computer time to scan the complete 360^{o} circle. Consequently, the program as written scans approximately 40^{o} centered near the assumed azimuth.

The scanner may be considered as having 48 "probes" spaced at 3^{o} intervals on its periphery. Consequently, its plane of symmetry occurs midway between two antennas, or when the boresight is an odd multiple of 1.5^{o}. When this condition prevails, the scanner as simulated is "lined up" on 48 antennas. When any other condition prevails, the scanner "probes" are not lined up, but in fact each "probe" receives signals from two different antennas. In this model a linear interpolation of voltage is assumed. The sequence of steps performed in the scanner model is outlined:

1. An initial boresight on a plane of symmetry, and about 20° less than the assumed azimuth, is chosen.
2. The set of 48 antennas "seen" by the scanner is determined.
3. Appropriate delays are added to the 48 signals which will be processed.
4. The 48 signals, as delayed, are resolved into real and quadrature axis components.
5. The 24 "left-side" signals are added, and the 24 "right-side" signals are added. The four results of this are stored in whatever fashion may be most useful in a particular case.
6. The scanner is rotated to the next sampling point, determined by the number of samples per revolution. The process is generally repeated but if this rotation is other than 3°, then the "probes" will not be lined up, and it is necessary to interpolate between signals on two adjacent antennas. An "interpolation fraction" is found; it is a number less than unity. Because the scanner rotates in the direction of increasing azimuth, this fractional part of the signal to the "right" (higher azimuthal direction) is used, and one minus this fractional part of the signal to the "left" is used. As a result, the set of 24 signals is derived from 25 antennas, except when this fraction is zero.
7. Note on delays: When the boresight and assumed azimuth are equal, and in addition equal to an odd multiple of 1.5°, then the delays

are such as to put all 48 signals into phase. This feature is useful for checking the programs.

The result of this process is a set of numbers which represents the real and quadrature axis components of the scanner output at each sampling point within the sector sampled. The remaining sampling points have negligible outputs, and are set to zero. Thus, if 360 samples per revolution are specified, 41 samples are fully evaluated, and the remaining 319 are set to zero. Because later processing will discard many of the 41 non-zero samples, this procedure is fully justified.

Figures 3, 4, and 5 show typical sets of data. In these computations, the magnitude of the sum of the left-side and right-side phasors has been determined. This then represents the amplitude of the output of the summing portion of the hybrid network.

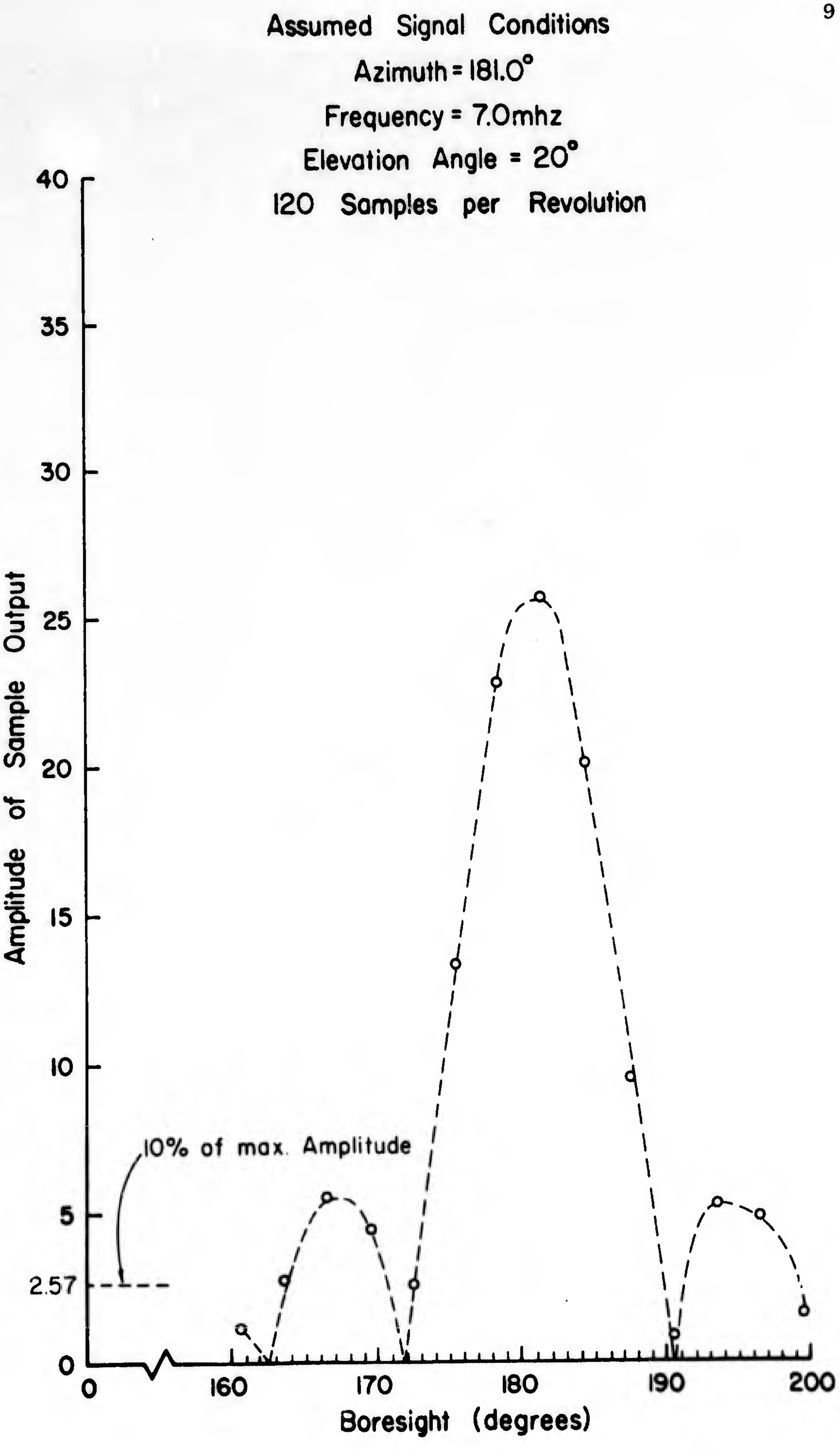


Figure 3. Simulated Antenna Scanner Output - Summing Mode

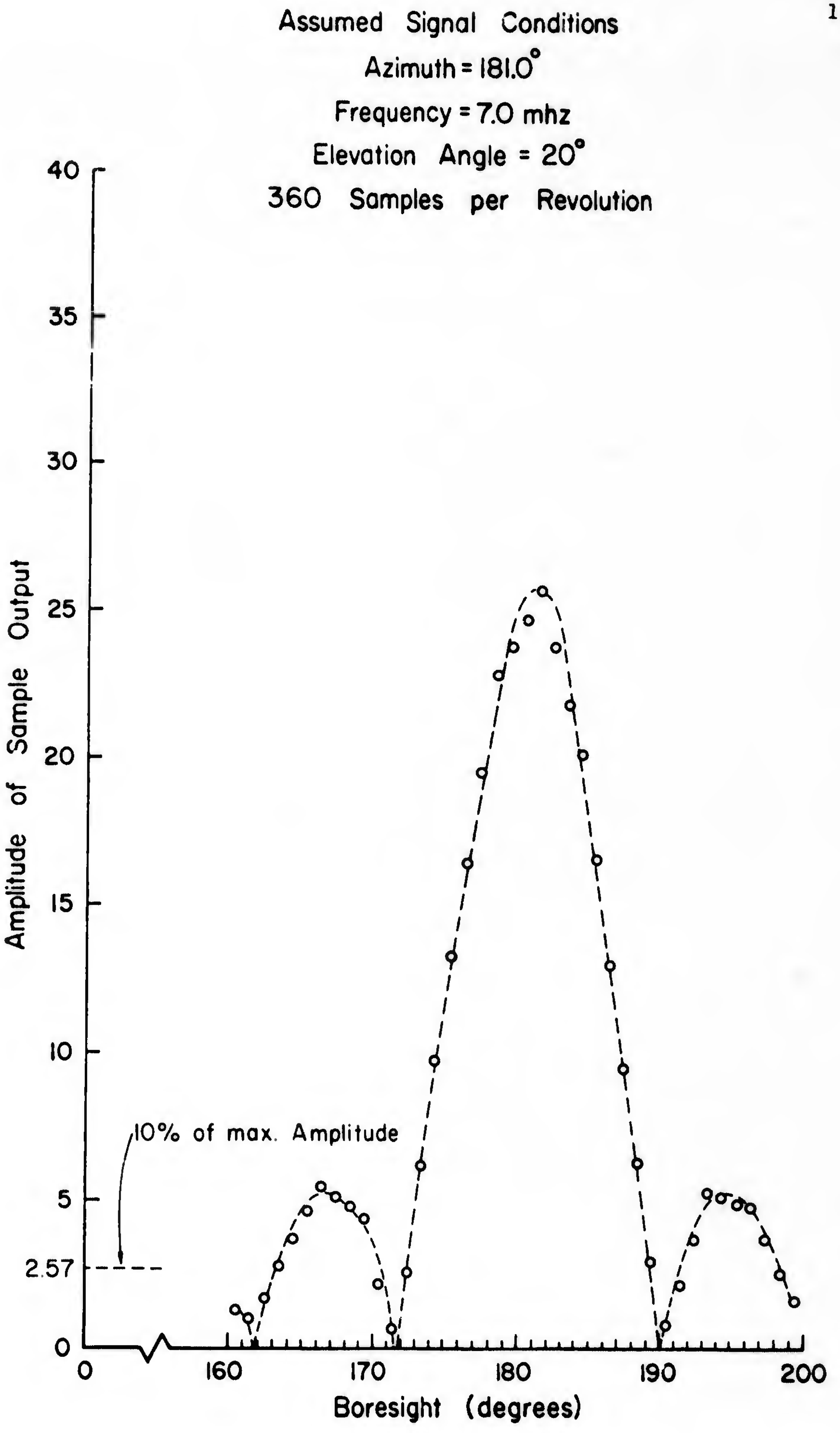


Figure 4. Simulated Antenna Scanner Output - Summing Mode

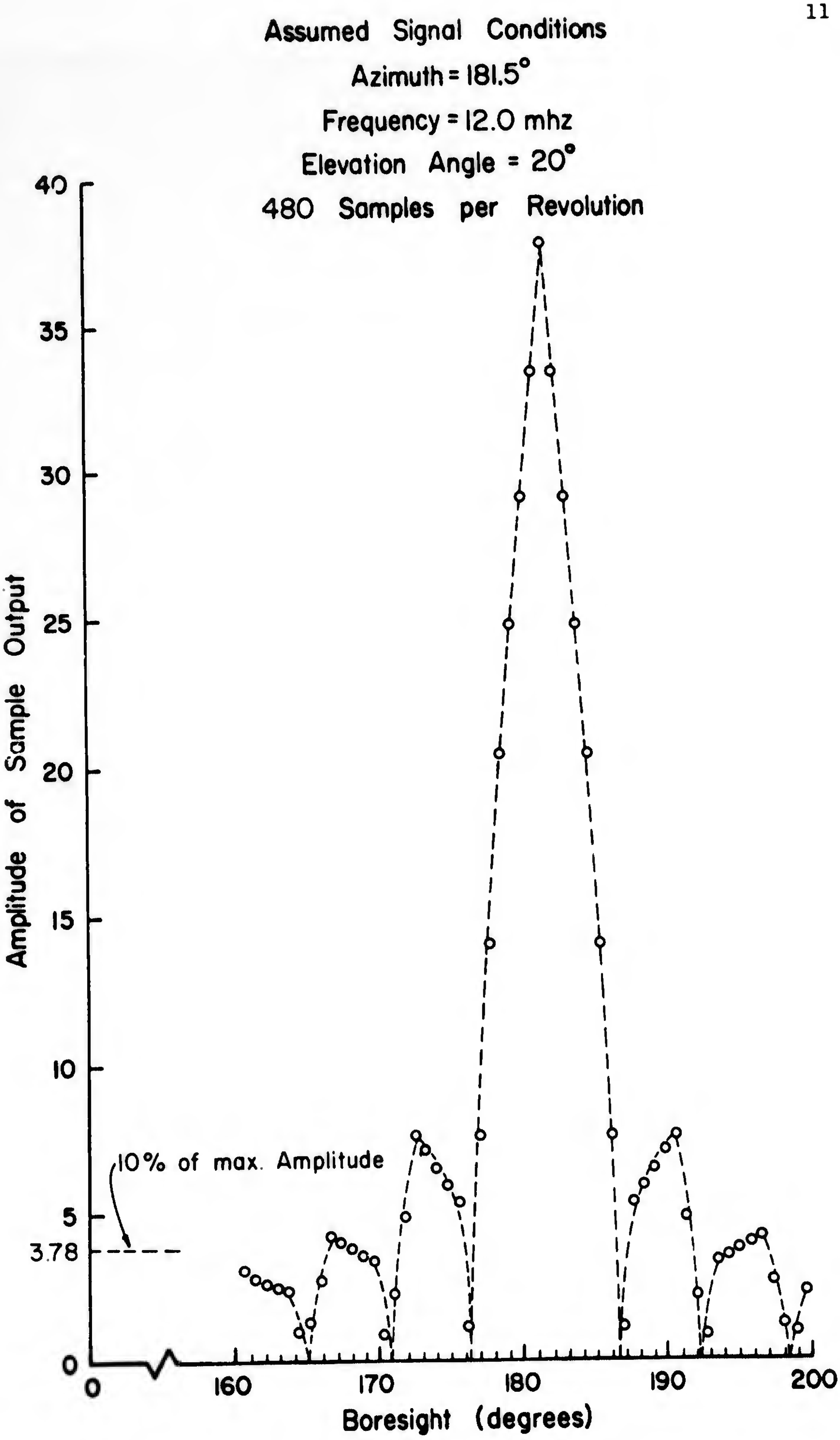


Figure 5. Simulated Antenna Scanner Output - Summing Mode

Bearing Calculation

The final portion of the program is concerned with the calculations of the apparent bearing, or azimuthal angle of arrival, of a signal from the set of points representing the scanner outputs as a function of boresight. The method chosen is based on the work of Smith[3], which he has termed the "center of gravity" method. The center of gravity, C, of a set of points $F(X_i)$ is given by

$$C = \frac{\sum_{i=1}^{n} X_i \cdot F(X_i)}{\sum_{i=1}^{n} F(X_i)}, \text{ where } X_i = i.$$

The formula is simple - the problem of implementation requires considerable care in its resolution.

The difficulty in implementation is to choose which n points to be considered in the calculation of the center of gravity. Smith[3] has shown that the best approach is to consider those points whose amplitude is greater than 10% of the difference between the maximum and minimum values. Since the minimum will ordinarily be much less than 1% of the maximum, this criterion can be effectively simplified to 10% of the maximum. All remaining points should be set to zero. But, more than this seems to be required.

Examination of Fig. 5 shows what might happen if this criterion were applied directly. Points near the minima of the principal lobe would be set to zero, but points in the second and third lobes would not. Another suggestion is to start near the center (at the largest sample), and progress to one side, until a sample smaller than 10% is found. Then, set this and all remaining samples on that side to zero. Repeat for the other side. But, in the case of high frequencies, it is easy to see that on one side, a number might be found very close to the minimum between the main lobe and the first side lobe, but on the other side, no small numbers before the third side lobe would be found. This would not happen if the samples were sufficiently close.

The problem then becomes one of determining the limits of the principal lobes, and doing this when the rotation between samples is an appreciable fraction of the width of the principal lobe. Two acceptable solutions for this have been found, and the choice between them depends on the desired number of sampling points per revolution, which in the interest of computing efficiency should be as small as possible.

A particularly desirable number of samples per revolution is 120, or 3 degrees of rotation between samples. Three degrees is the angular distance between the planes of symmetry. The scheme that has been found most successful is outlined in this set of steps.

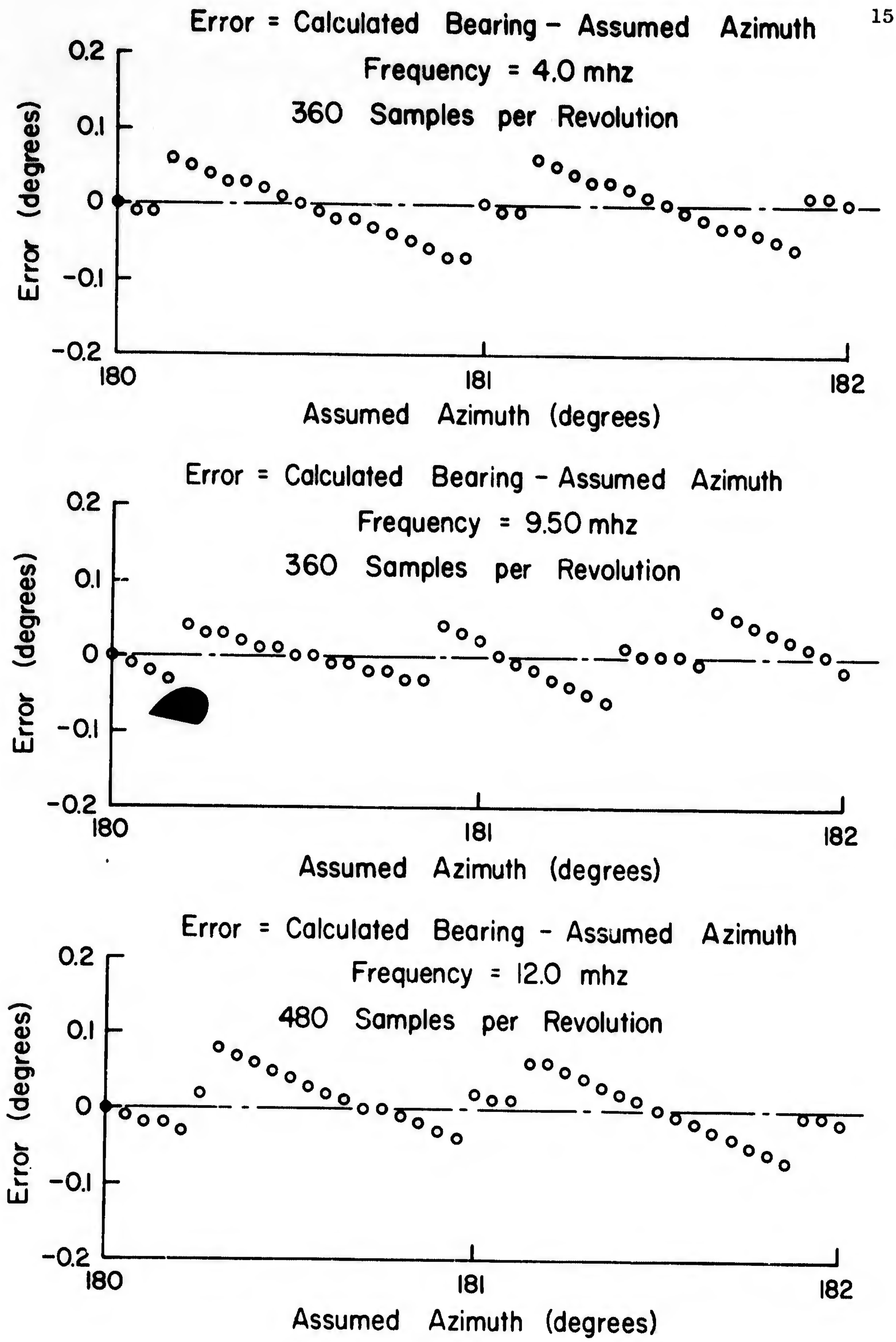
1. Determine the largest sample, and its location.
2. Compare, in pairs, the samples on either side of this maximum, while progressing away from the maximum.
3. When a sample is found that is less than 10% of the maximum, set it and all others farther from the maximum on that side to zero. If the corresponding sample on the other side is also less than 10% of the maximum, set it and all others on that side to zero. But if it is greater than 10%, retain it, but set all the others on that side to zero.
4. Reference to Fig. 3 shows that this scheme would retain the samples at 172.5°, 175.5°, 178.5°, 181.5°, 184.5° and 187.5°.

All others would be set to zero.

This gives good results - errors less than 0.2 degrees when the beamwidth at the 10% points is near an even multiple of 3 degrees, e.g., 5.1 mhz, 6.7 mhz but gives errors greater than 0.6 degree at odd multiples, e.g., 5.8 mhz, 7.8 mhz, and 12.0 mhz. The difficulty is primarily one of an insufficient number of samples - this varies from 9 at 4.0 mhz to 3 at 12.0 mhz. McAuley[4] has shown that any scheme giving less than 12 samples may be subject to this sort of difficulty, and so the reluctant decision to allow for more samples was made.

The final conclusion has been to choose a number of samples per revolution that will allow 12 or more significant samples to be retained before the bearing is computed. For frequencies up to 9.50 mhz, this requires 360 samples per revolution; for frequencies between 9.50 mhz and 12.0 mhz, 480 samples will be needed. When this is done, the sample rejection scheme is simplified, and it is possible to:

1. Determine the maximum sample, and its location.
2. Progress on one side until a sample less than 10% of the maximum is found. Set it and all remaining samples on that side to zero. repeat for the other side. The larger number of samples per revolution insures that the minimum between the main lobe and the side lobes will not be missed. By doing this, it is possible to keep the maximum error less than 0.1° in bearing over the frequency range 4.0 - 12.0 mhz. Figures 6, 7, and 8 show these errors at 4.0, 9.50, and 12.0 mhz. Because of symmetry, the information presented may be extended to any other azimuth.



Figures 6, 7, 8. Errors in Automatic Bearing Computer

A copy of the FORTRAN program as it existed in December 1965, forms the appendix to this report. It is hoped that the "comment" cards make the various sequences clear, and also their operation.

Many uses for this program are contemplated. The results of these studies will be subjects for future reports. Doing this may require slight modification of certain parts of the program--for example, no provision yet exists to study effects of two rays. This program has been written in FORTRAN-M(5); it may in the future be desirable to change it slightly so that it may be used in FORTRAN-IV.

REFERENCES

1. Interim Engineering Report on Wullenweber-type Antenna Array, Report No. 2 15 January 1957. (RRL TR 29, University of Illinois Reports).

2. P. S. Carter, "Antenna Arrays Around Cylinders", Proceedings Institute of Radio Engineers, Vol. 31, No. 12, pp. 671-693, December 1943.

3. R. S. Smith, Electronic Observers for Radio Direction Finding, (RRL Publication No. 273, University of Illinois Reports), Technical Report No. 11, Contract Nobsr 89229, February 1965.

4. R. McAulay, Some Relations Between Digitizing Parameters and Calculated Statistics of a Waveform, (RRL Publication No. 208, University of Illinois Reports), Technical Report No. 1, Contract Nobsr 89229, 15 August 1963.

5. G-20 FORTRAN - M/REFERENCE MANUAL, Control Data Corporation, October 1963.

APPENDIX

```
C     FIRST DATA CARD SHOWS GONIO SPEED IN RPM, SIMULATED TIME IN
C     SECONDS, AND SAMPLES PER REVOLUTION.    THE SECOND DATA CARD
C     CONTAINS THE ATTENUATION CONSTANT (ALPHA), THE CABLE LENGTH, AND
C     THE VELOCITY OF PROPAGATION AS A DECIMAL FRACTION OF FREE SPACE
C     VELOCITY.  NEXT TWO CARDS PROVIDE FOR STANDARD DEVIATIONS IN THREE
C     RANDOMLY VARIED QUANTITIES, WHICH MAY BE CHOSEN LATER, AND PROVIDE
C       INITIAL LOAD FOR THE RANDOM NUMBER GENERATOR.
C     THE REMAINING DATA CARDS CONTAIN THE AZIMUTH OF THE
C     ASSUMED INCOMING SIGNAL, ITS ASSUMED ELEVATION ANGLE, AND ITS
C     FREQUENCY IN MEGACYCLES PER SECOND.  THESE ARE IN THREE FIELDS,
C     EACH OF WHICH IS TEN COLUMNS WIDE.  THE LAST CARD IN THE DATA DECK
C     HAS -1.0 IN THE FIRST FIELD TO SIGNAL THE END OF THE DATA.
C     ********************
       DIMENSION LREAL(24),LIMAG(24),RREAL(24),RIMAG(24)
      DIMENSION A(120),P(120),REAL(120),IMAG(120),SAMP(720),ACCUM(720)
      DIMENSION DELAY(24),GONRE(720),GONIM(720)
      DIMENSION RVPROP(60)   ,RALPHA(60), RLNGTH(60)
      DIMENSION BRNG(11),CNTR(11)
      DIMENSION AZMUTH(41), ERROR(41)
C     ********************
      PI=3.14159265
      TWOPI=2*PI
      RAD=180/PI
      READ 200,GONSPD,TIME,SAMREV
      READ 200,ALPHA,LENGTH,VPROP
      READ 200, STDEV1,STDEV2,STDEV3
      READ 201, RAN
  200 FORMAT(3F10.0)
  201 FORMAT(I6)
      REV=GONSPD*TIME/60
      RN = RAN
    1 READ 200 ,AZM,THETA,FREQ
      COSTHE=COS(THETA/RAD)
      LAMBDA=300/FREQ
      NUMREV=1.
C     ********************
C     ARRAY FOR PLOT OF HISTOGRAM
C     ********************
      DO 501 I=1,11
      CNTR(I) = 0.0
  501 CONTINUE
      X = AZM - 0.60
      DO 502 I=1,11
      BRNG(I) = X + 0.1*I
  502 CONTINUE
      SUMBEA = 0.0
      SUMSQB = 0.0
      DO 59 I=1,SAMREV
      ACCUM(I)=0
   59 CONTINUE
```

```
      IF(AZM) 99,10,10
C     ********************
C     SIGNAL FROM DIRECTION AZM GOES TOWARDS ANTENNA K OR BETWEEN IT AND
C     THE FIRST ANTENNA TO THE RIGHT, ANTENNA K+1.
C     ********************
   10 K=INT(AZM/3)
      PHIK=AZM-K*3
      PHIL=3-PHIK
C     ********************
C     DIR=1 FOR ANTENNA K AND THOSE ANTENNAS LEFT OF K
C     DIR=2 FOR ANTENNAS TO THE RIGHT OF K
C     ********************
      DIR=1.0
   18 DO 11 I=1,30
      GO TO (12,13),DIR
   12 ANT=K+1-I
      IF(ANT)14,14,15
   14 ANT=120+ANT
   15 PHI=PHIK+3*(I-1)
      GO TO 19
   13 ANT=K+I
      IF(120-ANT)20,21,21
   20 ANT=ANT-120
   21 PHI=PHIL+3*(I-1)
   19 COSPHI=COS(PHI/RAD)
      A(ANT)=COSTHE*(SIN(TWOPI*5.94/LAMBDA*COSPHI*COSTHE))
      P(ANT)=TWOPI*145.5/LAMBDA*COSPHI*COSTHE
   11 CONTINUE
      IF(DIR-2) 16,17,17
   16 DIR=2
      ILEFT=ANT
      GO TO 18
   17 IRIGHT=ANT
C     ********************
C     SET UNUSED LOCATIONS OF ARRAYS A AND P TO ZERO
C     ********************
      DO 30 I=1,60
      ANT=IRIGHT+I
      IF(120-ANT) 31,32,32
   31 ANT=ANT-120
   32 A(ANT)=0.0
   30 P(ANT)=0.0
C     ********************
C     SIMULATION OF CABLES
C     ********************
      DO 42 I=1,60
      ANT=ILEFT+I-1
      IF(120-ANT) 43,44,44
   43 ANT=ANT-120
C     ********************
C     THE PROGRAM AS IT APPEARS HERE PERMITS STUDY OF EFFECTS OF RANDOM
```

```
C       VARIATIONS IN THE CABLE PARAMETERS
C       *********************
    44 RALPHA(I) = ALPHA*   (1 + RND(RN)*STDEV1)
       RLNGTH(I) = LENGTH*(1 + RND(RN)*STDEV2)
       RVPROP(I)= VPROP*(1 + STDEV3*RND(RN))
       A(ANT) = A(ANT)*EXP(-RALPHA(I)*RLNGTH(I))
       P(ANT) = P(ANT) - (TWOPI*FREQ*RLNGTH(I))/(300.0*RVPROP(I))
    42 CONTINUE
C       *********************
C       CONVERSION OF AMPLITUDES AND PHASES INTO REAL AND IMAG PARTS
C       COMMENT CARD USED TO INDICATE TEMPORARY OMISSION OF INSTRUCTIONS
C       DO 45 I=1,120
C       REAL(I)=A  (I)*COS(P(I))
C   45 IMAG(I)=A  (I)*SIN(P(I))
C       *********************
C       DELAYS
C       LOW BAND (4 - 12 MC)
C       24 PICKUPS ON EACH SIDE OF SCANNER
C       *********************
       PICKUP=24
       THETCP=20/RAD
C       *********************
C       MAXIMUM DELAY FOR ANY SIGNAL IN GONIO MODEL
C       *********************
       DELMAX = 145.5*COS(70.5/RAD)*TWOPI*FREQ/300
       DO 300 I=1,PICKUP
       ALI=(89.25-1.5*(I-1))/RAD
       BW =291.00*COS(ALI)*COS(ALI)*COS(THETOP)
       DELAY(I) = DELMAX - TWOPI*FREQ*BW/300
   300 CONTINUE
C       *********************
C       THIS GONIO MODEL PERMITS SAMPLING INTERVALS LESS THAN THREE DEGREE
C       AND PERMITS SCAN OF ABOUT 40 DEGREE SECTOR CENTERED NEAR THE
C       ASSUMED AZIMUTH.  SCHEME INVALID FOR AZIMUTHS WITHIN 25 DEGREES
C       OF NORTH.           SYMBOL IDENTIFCATION  DEGSAM = DEGREES
C       BETWEEN SAMPLES, ROSTRT = INITIAL POSITION OF ROTOR IN ITS SCAN,
C       L,K2,K3,K4 DEFINE SCAN LIMITS, L2 DEFINES ANTENNA THAT LEFT SIDE
C       OF GONIO IS SET ON, INTFR IS INTERPOLATION FRACTION
C       BORSIT IS BORESIGHT OF ASSUMED GONIO ROTOR POSITION
C       *********************
       DEGSAM = 360.0/SAMREV
       L = SAMREV/120
       K2 = INT(L*K)
       K3 = K2 - INT(SAMREV/20)
       K4 = K2 + 1 + INT(SAMREV/20 + L)
       ROSTRT = K2*DEGSAM - 19.5
       DO 312 ISAM = K3,K4
       BORSIT = ROSTRT + (ISAM - K3)*DEGSAM
       L2 = (BORSIT - 1.49999999999)/3
       NANT = INT(L2)
       INTFR = L2 - INT(L2)
```

```
C     ********************
C     LEFT HALF OF ROTOR
C     ********************
      DO 301 I = 1, PICKUP
      ANT = NANT - I + 1
      IF(ANT) 304,304,305
  304 ANT = ANT + 120
  305 ANT2 = ANT + 1
      A1 = A(ANT)
      A2 = A(ANT2)
      B1 = P(ANT) - DELAY(I)
      B2 =   P(ANT2) - DELAY(I)
      LREAL(I) = (1 - INTFR)* A1*COS(B1)  + INTFR*A2*COS(B2)
      LIMAG(I) = (1 - INTFR)*A1*SIN(B1) + INTFR*A2*SIN(B2)
  301 CONTINUE
C     ********************
C     RIGHT HALF OF ROTOR
C     ********************
      DO 302 I = 1, PICKUP
      ANT = NANT + I
      IF(120 - ANT) 307,306,306
  307 ANT = ANT - 120
  306 ANT3 = ANT + 1
      A3 = A(ANT)
      A4 = A(ANT3)
      B3 = P(ANT) - DELAY(I)
      B4 = P(ANT3) - DELAY(I)
      RREAL(I) = (1 - INTFR)*A3*COS(B3) + INTFR*A4*COS(B4)
      RIMAG(I) = (1 - INTFR)*A3*SIN(B3) + INTFR*A4*SIN(B4)
  302 CONTINUE
C     **********SUM REAL AND IMAGINARY PARTS
      SUMLR = 0.0
      SUMLI = 0.0
      SUMRR = 0.0
      SUMRI = 0.0
      DO 308 I = 1, PICKUP
      SUMLR = SUMLR + LREAL(I)
      SUMLI = SUMLI + LIMAG(I)
      SUMRR = SUMRR + RREAL(I)
      SUMRI = SUMRI + RIMAG(I)
  308 CONTINUE
      GONRE(ISAM) = SUMLR + SUMRR
      GONIM(ISAM) = SUMLI + SUMRI
      X = GONRE(ISAM)
      Y = GONIM(ISAM)
      SAMP(ISAM) = SQRT(X*X + Y*Y)
  312 CONTINUE
C     ********************
C     SET REMAINING GONIO SAMPLES TO ZERO, AS THEY ARE ASSUMED INSIGNIF-
C     ICANT COMPARED WITH THOSE NEAR THE ASSUMED AZIMUTH
C     ********************
```

```
      K8 = K3 - 1
      DO 315 ISAM = 1, K8
      SAMP(ISAM) = 0.0
  315 CONTINUE
      K9 = K4 + 1
      DO 316 ISAM = K9, SAMREV
      SAMP(ISAM) = 0.0
  316 CONTINUE
C     ********************
C     END OF GONIOMETER OR ANTENNA SCANNER SIMULATION
C
C
C     BEGINNING OF THE END
C     SEARCH FOR MAXIMUM SAMPLE
C     ********************
      MAX=SAMP(1)
      MIN = 0.0
      DO 47 I=2,SAMREV
      IF(SAMP(I) - MAX)  47,47,49
   49 MAX=SAMP(I)
      MAXSMP=I
   47 CONTINUE
      SIGNIF=0.1*(MAX-MIN)
C     ********************
C     DETERMINATION OF PRINCIPAL LOBE.  USE SEQUENCE BEGINNING WITH CARD
C     51 IF LESS THAN 360 SAMPLES PER REVOLUTION.  USE SEQUENCE
C     BEGINNING WITH CARD 52 IF 360 OR MORE SAMPLES PER REVOLUTION.
C     ********************
      IF(SAMREV - 360) 51,52,52
   51 IF(SAMP(MAXSMP + 1) - SAMP(MAXSMP)) 70,71,70
   70 DO 72 I = MAXSMP,K4
      J = 2*MAXSMP - I - 1
      TEMP1 = SAMP(I+1)
      TEMP2 = SAMP(J)
      IF(TEMP1 - TEMP2) 73,74,74
   73 IF(TEMP1 - SIGNIF) 75,72,72
   74 IF(TEMP2 - SIGNIF) 78,72,72
   72 CONTINUE
   75 IF(TEMP2 - SIGNIF) 751,752,752
  752 K5 = I + 1
      K6 = 2*MAXSMP -K5 - 1
      GO TO 80
   78 IF(TEMP1 - SIGNIF) 751,782,782
  782 K5 = I+2
      K6 = 2*MAXSMP - K5 + 1
      GO TO 80
  751 K5 = I + 1
      K6 = 2*MAXSMP - K5
   80 DO 76 I = K5,K4
      SAMP(I) = 0.0
   76 CONTINUE
```

```
      DO 77 I = K3,K6
      SAMP(I) = 0.0
   77 CONTINUE
      GO TO 79
   71 DO 82 I = MAXSMP,K4
      J = 2*MAXSMP - I - 1
      TEMP1 = SAMP(I+2)
      TEMP2 = SAMP(J)
      IF(TEMP1 - TEMP2)83,84,84
   83 IF(TEMP1 - SIGNIF) 85,82,82
   84 IF(TEMP2 - SIGNIF) 85,82,82
   82 CONTINUE
   85 K5 = I + 2
      DO 86 I = K5,K4
      SAMP(I) = 0.0
   86 CONTINUE
      K6 = 2*MAXSMP + 1 - K5
      DO 87 I = K3, K6
      SAMP(I) = 0.0
   87 CONTINUE
      GO TO 79
C     *********************
C     END OF SAMPLE REJECTION SCHEME WITH LESS THAN 360 SAMPLES PER REV.
C     *********************
   52 DO 55 I = MAXSMP,K4
      XA = SAMP(I) - SIGNIF
      IF(XA) 53,53,55
   55 CONTINUE
   53 K5 = I
      DO 56 I = K5,K4
      SAMP(I) = 0.0
   56 CONTINUE
      DO 58 I = MAXSMP,K4
      LU = 2*MAXSMP - I - 1
      XB = SAMP(LU) - SIGNIF
      IF(XB) 67,67,58
   58 CONTINUE
   67 K6 = LU
      DO 63 I = K3,K6
      SAMP(I) = 0.0
   63 CONTINUE
C     *********************
C     COMPUTE BEARING
C     *********************
   79 SUMN = 0.0
      SUMD=0
      GOA=1
      HALFSM=SAMREV/2
      IF(HALFSM-MAXSMP) 321,321,320
  320 SUB=-1*(MAXSMP-1)
      GO TO 322
```

```
  321 SUB=SAMREV-MAXSMP+1
  322 K=-1*(HALFSM)
      DO 323 I=1,SAMREV
      SUMD=SUMD+SAMP(I)
      GO TO (330,331),GOA
  330 J=I+SUB-1
      IF(HALFSM-J) 325,324,324
  325 GOA=2
  331 K=K+1
      J=K
  324 SUMN=SUMN+SAMP(I)*J
  323 CONTINUE
           BEARNG=(SUMN/SUMD+MAXSMP)*DEGSAM-1.5
      SUMSQB = SUMSQB + BEARNG*BEARNG
      SUMBEA = SUMBEA + BEARNG
      IF(BEARNG) 333,334,334
  333 BEARNG=360+BEARNG
  334 PRINT 103, BEARNG
  103 FORMAT(5X,11HBEARING OF   ,F6.2,8H DEGREES )
C     ********************
C     ACCUMULATE DATA POINTS
C     *********************
      DO 54 I=1,SAMREV
      ACCUM(I)=ACCUM(I)+SAMP(I)
   54 CONTINUE
C     *********************
C     DEVELOP DATA FOR HISTOGRAM  (USED WHEN EFFECTS OF RANDOM
C     VARIATIONS ARE STUDIED)
C     *********************
      ERR = BEARNG - AZM
      IF (ERR + 0.45) 503,504,504
  503 CNTR(1) = CNTR(1) + 1.0
      GO TO 530
  504 IF(ERR + 0.35) 505,506,506
  505 CNTR(2) = CNTR(2) + 1.0
      GO TO 530
  506 IF(ERR+0.25) 507,508,508
  507 CNTR(3) = CNTR(3) + 1.0
      GO TO 530
  508 IF (ERR + 0.15) 509,510,510
  509 CNTR(4) = CNTR(4) + 1.0
      GO TO 530
  510 IF(ERR + 0.05) 511,512,512
  511 CNTR(5) = CNTR(5) + 1.0
      GO TO 530
  512 IF (ERR - 0.05) 513,513,514
  513 CNTR(6) = CNTR(6) + 1.0
      GO TO 530
  514 IF (ERR-0.15) 515,515,516
  515 CNTR(7) = CNTR(7) + 1.0
      GO TO 530
```

```
  516 IF (ERR - 0.25) 517,517,518
  517 CNTR(8) = CNTR(8) + 1.0
      GO TO 530
  518 IF (ERR - 0.35) 519,519,520
  519 CNTR(9) = CNTR(9) + 1.0
      GO TO 530
  520 IF (ERR - 0.45) 521,521,522
  521 CNTR (10) = CNTR(10) + 1.0
      GO TO 530
  522 CNTR(11) = CNTR(11) + 1.0
  530 IF(REV-NUMREV) 60,60,61
   61 NUMREV = NUMREV+1
      GO TO 10
C     *******************
C     COMPUTE BEARING USING ACCUMULATED DATA
C     *******************
   60 SUMN=0
      SUMD=0
      MAX=ACCUM(1)
      DO 340 I=2,SAMREV
      IF(ACCUM(I)- MAX) 340,340,351
  351 MAX=ACCUM(I)
      MAXACC=I
  340 CONTINUE
      IF(HALFSM-MAXACC) 341,341,342
  342 SUB=-1*(MAXACC-1)
      GO TO 343
  341 SUB=SAMREV-MAXACC+1
  343 K=-1*(HALFSM)
      GOB=1
      DO 344 I=1,SAMREV
      SUMD=SUMD+ACCUM(I)
      GO TO (345,346),GOB
  345 J=I+SUB-1
      IF(HALFSM-J) 347,348,348
  347 GOB=2
  346 K=K+1
      J=K
  348 SUMN=SUMN+ACCUM(I)*J
  344 CONTINUE
      BEAR=(SUMN/SUMD+MAXACC)*DEGSAM- 1.5
      IF(BEAR) 349,350,350
  349 BEAR=360+BEAR
C     *******************
C     PERFORM SUMMARY CALCULATIONS
C     PRINT INPUT DATA AND RESULTS OF SIMULATION STUDY
C     *******************
  350 VP = 100.0*VPROP
      ST1 = 100.0*STDEV1
      ST2 = 100.0*STDEV2
      ST3 = 100.0*STDEV3
```

```
      RNA = RN
      BEARAV = SUMBEA/NUMREV
      BEARVA = SUMSQB/NUMREV - BEARAV*BEARAV
      IF(BEARVA) 540,541,541
  540 PRINT 290
      BEARVA = 0.0
  541 BEARSD = SQRT(BEARVA)
      IF(BEARAV) 550,551,551
  550 BEARAV = BEARAV + 360.0
  551 CONTINUE
C     ********************
  290 FORMAT(10X,25HNEGATIVE BEARING VARIANCE)
C     ********************
  220 FORMAT(1H1////10X, 19H ASSUMED SIGNAL AT , F6.2, 39H MEGACYCLES,
     1DIRECTION OF ARRIVAL IS      )
  230 FORMAT(11X     ,F6.2,  36H DEGREES, AND THE ELEVATION ANGLE IS,
     1 F6.2, 8H DEGREES  ///)
C     ********************
  221 FORMAT(10X,17H GONIO ROTATES AT,F8.2, 8H RPM FOR , F10.7, 18H SECO
     1NDS AND TAKES  )
  231 FORMAT(11X     ,I3  , 23H SAMPLES PER REVOLUTION  ///)
C     ********************
  222 FORMAT(10X, 22H THE CABLE LENGTHS ARE, F8.2, 8H METERS, ,38H THE V
     1ELOCITY OF SIGNAL PROPAGATION IS   )
  232 FORMAT(10X, F6.2,  60H PERCENT OF FREE SPACE VELOCITY, THE ATTENUA
     1TION CONSTANT IS , F6.2,  17H NEPERS PER METER   ///)
C     ********************
  223 FORMAT(10X,30H THE INITIAL RANDOM NUMBER IS , I6   ,35H ,THE STD D
     1EV IN THE ATTENUATION IS , F8.4,   )
  233 FORMAT( 10X,                          27H PERCENT, IN THE LENGTHS IS ,
     1 F8.4, 34H PERCENT, AND IN THE VELOCITIES IS  , F8.4, 8H PERCENT )
  234 FORMAT(10X, 37H THE FINAL RANDOM NUMBER ARGUMENT IS  , E19.12////)
C     ********************
  104 FORMAT (5X,20HAPPARENT BEARING IS ,F6.2, 8H DEGREES   /////)
  291 FORMAT(5X,11HAVERAGE OF , I4 ,25H BEARING CALCULATIONS IS ,F6.2,8H
     1 DEGREES  /////)
  292 FORMAT(5X,22HSTANDARD DEVIATION OF , I4 ,25H BEARING CALCULATIONS
     1IS ,F6.2,  8H DEGREES  /////)
C     ********************
  229 FORMAT(10X, I3, 46H BEARING CALCULATIONS IN INCREMENT CENTERED ON
     1, F7.2, 8H DEGREES   )
C     ********************
      PRINT 220, FREQ
      PRINT 230, AZM, THETA
      PRINT 221, GONSPD, TIME
      PRINT 231, SAMREV
      PRINT 222, LENGTH
      PRINT 232, VP, ALPHA
      PRINT 223, RAN,ST1
      PRINT 233, ST2,ST3
      PRINT 234, RNA
```

```
      PRINT 104,BEAR
      PRINT 291,NUMREV,BEARAV
      PRINT 292,NUMREV,BEARSD
      DO 228 JI = 1,11
      PRINT 229, CNTR(JI), BRNG(JI)
  228 CONTINUE
      PLOT BRNG,CNTR
      PRINT 250, NUMREV
  250 FORMAT(1H1//10X, 31H CHOOSE NEW SIGNAL AND COMPUTE ,I4,9H BEARINGS
     1///)
      GO TO 1
 99   CONTINUE
      STOP
      END
```