NASA CONTRACTOR REPORT

NASA CR-2399

COMPUTER PROGRAM FOR THIN-WIRE STRUCTURES IN A HOMOGENEOUS CONDUCTING MEDIUM

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • JUNE 1974

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA CR-2399		
4. Title and Subtitle COMPUTER PROGRAM FOR THIN-WIRE STRUCTURES IN A HOMOGENEOUS CONDUCTING MEDIUM		5. Report Date June 1974
		6. Performing Organization Code
7. Author(s) J. H. Richmond		8. Performing Organization Report No. TR 2902-12
		10. Work Unit No. 502-33-13-02
9. Performing Organization Name and Address The Ohio State University ElectroScience Laboratory Columbus, Ohio 43212		11. Contract or Grant No. NGL 36-008-138
		13. Type of Report and Period Covered Contractor Report
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		14. Sponsoring Agency Code
15. Supplementary Notes Topical report.		

16. Abstract

A computer program is presented for thin-wire antennas and scatterers in a homogeneous conducting medium. The analysis is performed in the real or complex frequency domain. The program handles insulated and bare wires with finite conductivity and lumped loads. The output data includes the current distribution, impedance, radiation efficiency, gain, absorption cross section, scattering cross section, echo area and the polarization scattering matrix. The program uses sinusoidal bases and Galerkin's method.

17. Key Words (Suggested by Author(s))		18. Distribution Statement	
Antennas, Spacecraft and Aircraft Antennas Applied Electromagnetic Theory		Unclassified - Unlimited STAR Category 09	
19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	52	$3.75

*For sale by the National Technical Information Service, Springfield, Virginia 22151

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I. INTRODUCTION

Reference 1 presents the electromagnetic theory for a thin-wire structure in a homogeneous conducting medium, and this report presents the corresponding computer program. The program performs a frequency-domain analysis of thin-wire antennas and scatterers. The wire configuration is a generalized polygon assembled from straight wire segments. The program has been tested extensively with simple structures (linear dipoles, V dipoles, coupled dipoles, square loops, octagonal loops, multiturn loops and coupled loops) and complicated configurations including wire-grid models of plates, spheres, cones, aircraft and ships. Although the air-earth or air-water interface is not considered, the program is applicable in many problems involving buried or submerged antennas or targets. It is useful in locating the poles of the admittance or scattering function for wire structures in the complex frequency domain.

A piecewise-sinusoidal expansion is used for the current distribution. The matrix equation ZI = V is generated by enforcing reaction tests with a set of sinusoidal dipoles located in the interior region of the wire. Since the test dipoles have the same current distribution as the expansion modes, this may be regarded as an application of Galerkin's method. Rumsey's reaction concept was most helpful in this development, and therefore the formulation is known as the "sinusoidal reaction technique."

The current is assumed to vanish at the endpoints (if any) of the wire, and Kirchhoff's current law is enforced everywhere on the structure. The input data specify the frequency, wire radius, wire conductivity, the parameters of the exterior medium, coordinates of points to describe the shape and size of the wire configuration, and a list of the wire segments. If some or all of the wire segments are insulated, the radius and permittivity of the insulating sleeve are indicated.

Coordinates are required for wire endpoints, corners, junctions and terminals. For accuracy, the longest wire segment should not greatly exceed one-quarter wavelength. Longer segments should be subdivided by defining additional current-sampling points. The program automatically defines a set of N sinusoidal dipole modes on the wire structure and computes the mutual impedance matrix for these modes. The elements in the matrix are generated by numerical integration when appropriate, or from closed-form expressions in terms of exponential integrals. The computer program uses certain approximations which yield a symmetric matrix even when the wire structure has finite conductivity, lumped loads and insulating sleeves.

In antenna problems, the output data includes the current distribution, impedance, radiation efficiency, gain, patterns and near-zone field. In bistatic scattering problems, the output includes the echo area and the complex elements of the polarization scattering matrix. In backscatter situations, the output includes also the absorption, scattering and extinction cross sections.

If the wire has finite conductivity or dielectric sleeves, it is assumed that the frequency is real. This restriction can readily be removed if the user will specify the surface impedance of the wire and the complex permittivities of the dielectric sleeves and the ambient medium appropriate for complex frequencies.

The user may make a tradeoff between accuracy and computation costs by specifying the input variable INT. A large value increases the accuracy and the cost. For most problems, the recommended value is INT = 4.

The program was run on an IBM 370/165 computer to determine the broadside backscatter for a wire-grid square plate with edge length L. With a five-by-five grid, there are 60 segments, 36 points and 84 simultaneous equations. With INT = 4, calculations were made for L/λ = 0.3, 0.4, 0.5, 0.6 and 0.7. The execution time was 100 seconds. This averages to 20 seconds for each value of L/λ. The wire structure was perfectly conducting, uninsulated and located in free space. No advantage was taken of the target symmetries.

The next section presents the thin-wire computer program, instructions for the user, typical input and output data and tables of the mutual impedance of sinusoidal dipoles. Appendicies list the computer subroutines and explain their functions.

II. THE THIN-WIRE COMPUTER PROGRAM

Fig. 1 is a Fortran listing of the thin-wire computer program. Near the beginning of this program, the DIMENSION statements reserve storage for a wire structure with up to 50 segments, 55 points and 60 dipole modes. Quantities with the same or related dimensions are grouped together on the same line or consecutive lines.

NM denotes the actual number of monopoles (segments), INM is the corresponding dimension, and the dimension for CG, VG and ZLD is twice INM. The second subscript for MD always has a dimension of 4.

N denotes the number of simultaneous linear equations and ICJ is the corresponding dimension. The dimension for C is (ICJ*ICJ + ICJ)/2.

The DO LOOP ending at statement 15 sets ISC(J) = 0 for all the segments. This indicates that the wires are bare or uninsulated. If some or all of the segments are insulated, the user may set ISC(J) = 1 for the appropriate segment numbers J.

```
      COMPLEX EP2,EP3,ETA,GAM,Y11,Z11,ZS
      COMPLEX EPPS,EPTS,ETPS,ETTS,EX,EY,EZ
      COMPLEX C(1830),CJ(60),EP(60),ET(60),EPP(60),ETT(60)
      DIMENSION I1(60),I2(60),I3(60),JA(60),JB(60)
      COMPLEX CGD(50),SGD(50),CG(100),VG(100),ZLD(100)
      DIMENSION D(50),IA(50),IB(50),ISC(50),MD(50,4),ND(50)
      DIMENSION X(55),Y(55),Z(55)
      DATA PI,TP/3.14159,6.28318/
      DATA E0,U0/8.854E-12,1.2566E-6/
    2 FORMAT(1X,8F15.7)
    3 FORMAT(1X,4F15.7/)
    4 FORMAT(1X,1I5,8F14.6)
    5 FORMAT(1H0)
    6 FORMAT(1X,6F15.7/)
    7 FORMAT(8F10.5)
    8 FORMAT(1X,1I4,13I5)
    9 FORMAT(3X,'MAX = ',I5,3X,'MIN = ',I5,3X,'N = ',I5)
      ICJ=60
      INM=50
      DO 15 J=1,INM
   15 ISC(J)=0
      READ(5,7)BM,ER2,SIG2,TD2
      WRITE(6,2)BM,ER2,SIG2,TD2
      READ(5,7)AM,CMM,ER3,SIG3,TD3
      WRITE(6,2)AM,CMM,ER3,SIG3,TD3
      READ(5,8)IBISC,IGAIN,INEAR,ISCAT,IWR,NGEN,NM,NP
      WRITE(6,8)IBISC,IGAIN,INEAR,ISCAT,IWR,NGEN,NM,NP
      READ(5,7)FMC,PHA,THA,PHI,THI,PHS,THS
      WRITE(6,2)FMC,PHA,THA,PHI,THI,PHS,THS
      DO 22 J=1,NM
      READ(5,8)IA(J),IB(J)
   22 WRITE(6,8)J,IA(J),IB(J)
      DO 40 I=1,NP
      READ(5,7)X(I),Y(I),Z(I)
   40 WRITE(6,4)I,X(I),Y(I),Z(I)
      READ(5,7)XP,YP,ZP
      FHZ=FMC*1.E6
      OMEGA=TP*FHZ
      IF(SIG2.LT.0.)EP2=ER2*E0*CMPLX(1.,-TD2)
      IF(TD2.LT.0.)EP2=CMPLX(ER2*E0,-SIG2/OMEGA)
      IF(SIG3.LT.0.)EP3=ER3*E0*CMPLX(1.,-TD3)
      IF(TD3.LT.0.)EP3=CMPLX(ER3*E0,-SIG3/OMEGA)
      ETA=CSQRT(U0/EP3)
      GAM=OMEGA*CSQRT(-U0*EP3)
      CALL SORT(IA,IB,I1,I2,I3,JA,JB,MD,ND,NM,NP,N,MAX,MIN,ICJ,INM)
      WRITE(6,5)
      WRITE(6,9)MAX,MIN,N
      WRITE(6,5)
      IF(MAX.GT.4 .OR. MIN.LT.1 .OR. N.GT.ICJ)GO TO 800
      INT=4
      I12=1
      DO 60 J=1,NM
      VG(J)=(.0,.0)
      ZLD(J)=(.0,.0)
      JJ=J+NM
      VG(JJ)=(.0,.0)
   60 ZLD(JJ)=(.0,.0)
      IF(NGEN.GT.0)VG(NGEN)=(1.,0.)
      CALL      SGANT(IA,IB,INM,INT,ISC,I1,I2,I3,JA,JB,MD,N,ND,NM,NP
     2,AM,BM,C,CGD,CMM,D,EP2,EP3,ETA,FHZ,GAM,SGD,X,Y,Z,ZLD,ZS)
      IF(N.LE.0)GO TO 800
      IF(NGEN.LE.0)GO TO 400
```

Fig. 1a. The thin-wire computer program.

```
      CALL GANT1(IA,IB,INM,IWR,I1,I2,I3,I12,JA,JB,MD,N,ND,NM,AM
     2,C,CJ,CG,CMM,D,EFF,GAM,GG,CGD,SGD,VG,Y11,Z11,ZLD,ZS)
      WRITE(6,3)EFF,GG,Z11
  200 IF(INEAR.LE.0)GO TO 300
      CALL       GNFLD(IA,IB,INM,I1,I2,I3,MD,N,ND,NM,AM,CGD,SGD,ETA,GAM
     2,CJ,D,X,Y,Z,XP,YP,ZP,EX,EY,EZ)
      WRITE(6,3)XP,YP,ZP
      WRITE(6,6)EX,EY,EZ
  300 IF(IGAIN.LE.0)GO TO 400
      INC=0
      PH=PHA
      TH=THA
      CALL       GFFLD(IA,IB,INC,INM,IWR,I1,I2,I3,I12,MD,N,ND,NM,AM
     2,ACSP,ACST,C,CGD,CG,CJ,CMM,D,ECSP,ECST,EP,ET,EPP,ETT,EPPS,EPTS
     3,ETPS,ETTS,GG,GPP,GTT,PH,SGD,SCSP,SCST,SPPM,SPTM,STPM,STTM,TH
     4,X,Y,Z,ZLD,ZS,ETA,GAM)
      WRITE(6,3)PH,TH,GPP,GTT
  400 IF(ISCAT.LE.0)GO TO 600
      INC=1
      PH=PHI
      TH=THI
      CALL       GFFLD(IA,IB,INC,INM,IWR,I1,I2,I3,I12,MD,N,ND,NM,AM
     2,ACSP,ACST,C,CGD,CG,CJ,CMM,D,ECSP,ECST,EP,ET,EPP,ETT,EPPS,EPTS
     3,ETPS,ETTS,GG,GPP,GTT,PH,SGD,SCSP,SCST,SPPM,SPTM,STPM,STTM,TH
     4,X,Y,Z,ZLD,ZS,ETA,GAM)
      WRITE(6,6)PH,TH,SPPM,SPTM,STPM,STTM
      WRITE(6,6)ACSP,ACST,ECSP,ECST,SCSP,SCST
  500 IF(IBISC.LE.0)GO TO 600
      INC=2
      PH=PHS
      TH=THS
      CALL       GFFLD(IA,IB,INC,INM,IWR,I1,I2,I3,I12,MD,N,ND,NM,AM
     2,ACSP,ACST,C,CGD,CG,CJ,CMM,D,ECSP,ECST,EP,ET,EPP,ETT,EPPS,EPTS
     3,ETPS,ETTS,GG,GPP,GTT,PH,SGD,SCSP,SCST,SPPM,SPTM,STPM,STTM,TH
     4,X,Y,Z,ZLD,ZS,ETA,GAM)
      WRITE(6,6)PH,TH,SPPM,SPTM,STPM,STTM
  600 CONTINUE
  800 CALL EXIT
      END
```

Fig. 1b. The thin-wire computer program.

The first READ statement inputs the following parameters for the dielectric insulation:

BM	outer radius in meters
ER2	dielectric constant relative to free space
SIG2	conductivity in mhos per meter
TD2	loss tangent

The program will use SIG2 or TD2 but not both. The user determines which one will be used by assigning the other a negative value. For an uninsulated wire structure, the program will not use any of the data from the first READ statement.

The second READ statement inputs the following parameters for the wire and the exterior medium:

AM	wire radius in meters
CMM	wire conductivity in megamhos per meter
ER3	dielectric constant relative to free space
SIG3	conductivity in mhos per meter
TD3	loss tangent

The parameters ER3, SIG3 and TD3 are those of the homogeneous ambient medium. Again, the program will use SIG3 or TD3 but not both.

The third READ statement inputs the following data:

IBISC	indicator for bistatic scattering calculations
IGAIN	indicator for antenna gain calculations
INEAR	indicator for near-zone field calculations
ISCAT	indicator for backscatter calculations
IWR	indicator for writeout of current distributions
NGEN	indicator for antenna calculations
NM	number of monopoles (segments)
NP	number of points

For each indicator, a positive value means the calculation or writeout is desired while a zero or negative value means it is not desired.

The fourth READ statement inputs the following data:

FMC	frequency in megahertz
PHA,THA	far-field angle for antenna gain
PHI,THI	incidence angle for plane-wave scattering
PHS,THS	scattering angle for bistatic scattering

The above angles are given in degrees, and they denote values of the angular coordinates in the spherical system (r,θ,ϕ) widely used in antenna and scattering literature.

The fifth READ statement (in the DO LOOP ending with statement 22) inputs the endpoints IA(J) and IB(J) of segment J. Thus, IA and IB are the index numbers of the two points which are joined by segment J.

The sixth READ statement (in the DO LOOP ending with statement 40) inputs the coordinates X(I), Y(I) and Z(I) of point I in meters. The seventh and last READ statement inputs the coordinates XP, YP and ZP (in meters) of the observation point for near-zone field calculations.

Some of the quantities used in the program are defined as follows:

FHZ	frequency in Hertz
OMEGA	angular frequency
EP2	complex permittivity of insulation
EP3	complex permittivity of ambient medium
ETA	intrinsic impedance of ambient medium
GAM	intrinsic propagation constant of ambient medium
ZS	surface impedance of wire

For an uninsulated wire with perfect conductivity, one may specify complex values for ETA and GAM and delete the following input data and calculations: BM, ER2, SIG2, TD2, ER3, SIG3, TD3, FMC, FHZ, OEMGA, EP2 and EP3.

After reading the input data, the program calls subroutine SORT. This subroutine defines a set of dipole modes on the wire structure. N denotes the total number of dipole modes, the number of simultaneous linear equations, and the size of the impedance matrix Z_{ij}. Since this matrix is symmetric, only the upper-right triangular portion (including the entire principal diagonal) is calculated and stored in C(K). SORT calculates N, but the user may predict N as follows to reserve adequate storage. If m wire segments intersect at a point, this point is defined as a junction of order m and degree n = m - 1. There will be n dipole modes with terminals at this junction. N is determined by summing the degrees of all the junctions. For an example, an endpoint of a dipole is a junction of order m = 1 and degree n = 0. The vertex of a V dipole is a junction of order 2 and degree 1. NP denotes the number of points on the wire structure, and each of these points is considered to be a junction.

Mode I is a two-segment V dipole with a sinusoidal current distributed over the intersecting segments JA(I) and JB(I). The dipole has endpoints I1(I) and I3(I) and terminals at I2(I). The reference direction for positive current on dipole I is from I1 to I2 to I3.

A wire segment may be shared by as many as four dipole modes, or as few as one. In the output of subroutine SORT, ND(J) denotes the number of dipoles sharing segment J. The extreme values of ND(J) are MAX and MIN. If MIN is less than one, the wire structure has an unconnected segment and the computation is aborted. (An isolated wire must have at least two segments and three points.) If N exceeds ICJ, the dimensions are inadequate and the run is aborted.

INT specifies the number of intervals for calculating the elements in the impedance matrix with Simpson's-rule integration. A large value for INT improves the accuracy at the expense of greater execution time. For most problems a suitable combination of speed and accuracy is obtained with INT = 4. A larger value is recommended if one wire passes close to another as in the helix or the multiturn loop. If in doubt, one may set INT = 0 to choose the rigorous closed-form impedance expressions in terms of exponential integrals.

The DO LOOP ending with statement 60 sets all the lumped load impedances and generator voltages to zero. If the wire structure has lumped loads, one may insert a READ command after statement 60 to input a list of complex load impedances ZLD(J). For a wire antenna with just one generator, the program inserts a unit voltage generator with VG(NGEN) = (1.,0.). If the antenna or array has several generators, one may insert a READ command after statement 60 to input a list of complex voltages VG(J).

Generators or lumped loads may be inserted at either end or both ends of segment J. First consider a load impedance inserted in the middle of segment J. Now slide the load along the segment and let it approach the endpoint IA(J). This load is represented by ZLD(J). Next insert another load in segment J and slide it to approach the endpoint IB(J). This load is designated ZLD(JJ) where JJ = J + NM. The same convention is employed for the voltage generators VG(J) and VG(JJ). A generator voltage VG(J) is considered positive if it tends to force a current flow in the direction from IA(J) to IB(J).

Subroutine SGANT calculates the elements of the impedance matrix Z_{ij} and stores them in C(K) where K = (I-1)*N - (I*I - I)/2 + J. This subroutine will set N = 0 and the run will abort if the wire radius is zero or negative, the shortest segment length is less than the wire diameter, the wire radius is electrically large, or the longest segment is too long.

Subroutine GANT1 considers the thin-wire structure as an antenna and solves for the current distribution CG(J), radiation efficiency EFF, time-average power input GG and complex power input Y11. In the current distribution, CG(J) is the current on segment J as one approaches the endpoint IA(J) and CG(JJ) is the current at the other end IB(J). The reference direction for positive current is from IA to IB. Thus, the conventions are the same for the branch currents CG and the branch voltages VG.

If the antenna has only one voltage generator with VG(NGEN) = (1.,0.), then Y11 is the antenna admittance and Z11 is the impedance.

The radiation efficiency EFF is calculated from the time-average power input to the antenna and the time-average power dissipated in the wire and the lumped loads. If the antenna is insulated, the power dissipated in the insulation is neglected. If the wire has perfect conductivity and the loads are purely reactive, the calculated efficiency will be 100 per cent.

The near-field subroutine GNFLD calculates the electric field intensity (EX,EY,EZ) at the observation point (XP,YP,ZP). In the calling parameters, CJ denotes the current distribution on the wire. (The loop currents are stored in CJ(I) and the branch currents in CG(J)). Thus, the currents must be calculated before GNFLD is called. Fig. 1 illustrates the use of GNFLD to calculate the near-zone field in an antenna problem. This subroutine can be called again just above statement 500 to calculate the near-zone scattered field for a wire target. In the calling parameters, CJ is replaced with EP or ET to obtain the near-zone field with a phi-polarized or theta-polarized incident plane wave. Reference 1 describes the more sophisticated techniques required when the observation point is extremely close to the wire structure.

The far-field subroutine GFFLD calculates antenna gain if INC = 0, backscattering if INC = 1, and bistatic scattering if INC = 2. If INC = 0, PH and TH denote the spherical coordinates ϕ and θ of the distant observation point and the output from GFFLD is defined as follows. EPPS and ETTS denote the phi-polarized and theta-polarized components of the electric field intensity. For example,

(1) $$\text{EPPS} = r\, e^{\gamma r}\, E_{\phi}$$

where r is the distance from the origin to the observation point. GPP and GTT denote the power gains associated with the phi and theta polarizations. Appendix 14 defines GPP and GTT more precisely.

If INC = 1, PH and TH denote the incidence angles ϕ_i and θ_i. These are also the spherical coordinates of the distant source.[1] In this backscattering situation, the output data from GFFLD are defined as follows:

ACSP,ACST	absorption cross sections for ϕ and θ polarizations
ECSP,ECST	extinction cross sections for ϕ and θ polarizations
EP,ET	loop currents induced by ϕ and θ polarized waves
EPPS	scattered electric field $E_{\phi\phi}$
EPTS	scattered electric field $E_{\phi\theta}$
ETPS	scattered electric field $E_{\theta\phi}$
ETTS	scattered electric field $E_{\theta\theta}$
SCSP,SCST	scattering cross sections for ϕ and θ polarizations
SPPM	echo area $\sigma_{\phi\phi}$

SPTM	echo area $\sigma_{\phi\theta}$
STPM	echo area $\sigma_{\theta\phi}$
STTM	echo area $\sigma_{\theta\theta}$

The echo areas are given in square meters. For the doubly-subscripted quantities such as $E_{\phi\phi}$ and $\sigma_{\phi\phi}$, the first and second subscripts specify the polarizations of the incident and scattered waves, respectively. The complex numbers EPPS, EPTS, ETPS and ETTS are the elements of the polarization scattering matrix.

If INC = 2, PH and TH denote the scattering angles ϕ_S and θ_S. These are the spherical coordinates of the distant observer. In this bistatic scattering situation, the only outputs from GFFLD are the polarization scattering matrix and the echo areas.

To obtain antenna patterns, backscattering patterns or bistatic patterns, one may insert DO LOOPS in the program to increment the angles PH and TH. The DO LOOP will begin just above the call to GFFLD and terminate just below this call. To obtain the near-zone field distribution along a given probing path, one may insert a DO LOOP beginning just above the call to GNFLD and terminating just below this call.

When the calculations have been completed for one problem, one may GO TO a point just above CALL GANT1 if only the generator voltages are to be changed. One may GO TO a point just below CALL SORT if there is a change in the wire radius or conductivity, the insulation, ambient medium, frequency, load impedances or the coordinates (X,Y,Z). If there is a change in NM, NP, IA or IB, one should GO TO a point above CALL SORT.

Consider an array of three center-fed dipoles, and suppose we desire the 3 x 3 admittance matrix for the array. Let each dipole be divided into four segments with segments 1 through 4 on dipole 1, 5 through 8 on dipole 2 and 9 through 12 on dipole 3. The three-port admittance matrix can be obtained by inserting a DO LOOP beginning just above CALL GANT1 and terminating just below this call. GANT1 will be called three times with all the voltages VG set to zero except for a single one-volt generator. On the first, second and third calls, let NGEN = 3, 7 and 11 to represent a generator at the center of dipole 1, 2 and 3, respectively. After the first call, set Y11 = CG(3), Y12 = CG(7) and Y13 = CG(11). Set Y22 = CG(7) and Y23 = CG(11) after the second call and Y33 = CG(11) after the third call.

For extremely small antennas, quasi-static or double-precision subroutines are required.

The wire radius must exceed zero, but there is no difficulty with small radii. If the radius exceeds 0.007λ, the thin-wire assumptions are questionable and the accuracy and convergence deteriorate. The length ratio of the longest and shortest segments should not exceed 100. It is assumed that the wire length exceeds the wire diameter by a factor of at least 30. We are not aware of any lower limit on the segment length, however.

If a wire is bent sharply to form a small acute angle (less than 30 degrees), the thin-wire model is questionable. It is assumed that the wire conductivity greatly exceeds the conductivity of the ambient medium. For insulated wires, the dielectric layer is assumed to be electrically thin.

For each thin-wire problem, calculations should be repeated several times with the wire divided progressively into shorter segments. There is no assurance of accuracy until the output data converge. For a moderately thick wire (with radius a = 0.007 λ or larger), the susceptance may diverge with the delta-gap model. This difficulty may be alleviated or eliminated with the magnetic-frill model and the techniques of Imbriale and Ingerson [2].

Tables 1, 2 and 3 list input and output data for three simple examples of uninsulated wire structures. Each table includes a sketch of the wire configuration with labels to indicate the numbering system for the points and segments. In these examples there are no lumped loads.

In the sinusoidal-reaction formulation, a basic function is the mutual impedance between two sinusoidal filamentary electric dipoles. One dipole is a test source located on the axis of the wire structure, and the other is an expansion mode on the wire surface. In view of the importance of this mutual impedance, short tables are presented next for a few simple cases. The data can be reproduced with the program in Fig. 1 with appropriate input data for uninsulated wires with perfect conductivity and no lumped loads in free space. The data were obtained with the closed-form expressions (INT = 0) by writing out the quantities C(K) just below the call to subroutine SGANT. Double precision was used for these calculations.

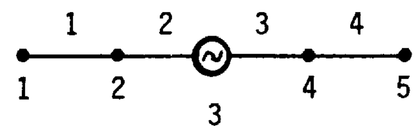
Table 4 lists the self impedance of a two-segment sinusoidal V dipole with radius a = 0.001 λ. Subroutine SGANT calculates this quantity by setting up one filamentary dipole on the wire axis and another identical dipole on the wire surface. These dipoles lie in parallel planes separated by a distance equal to the wire radius.

In Table 5, dipoles 1 and 2 have terminals at vertices 1 and 2, respectively, and they share the middle segment. Again these dipoles lie in parallel planes separated by a distance equal to the wire radius. For a one-turn planar polygon wire loop, subroutine SGANT would generate the data in Table 4 for the diagonal elements Z_{ii} and the data in Table 5 for the next elements.

TABLE 1
Input and Output Data for Straight Wire

Input Data

0.002	2.56	-1.0	0.0005				
0.001	1.00	1.0	-1.0	0.0			
1	1	1	1	0	3	4	5
300.	0.	90.	0.	90.	45.	45.	
1	2						
2	3						
3	4						
4	5						
0.	0.	-0.250					
0.	0.	-0.125					
0.	0.	0.					
0.	0.	0.125					
0.	0.	0.250					
1.	1.	1.					



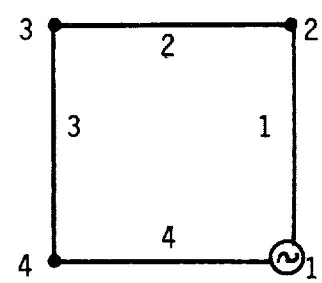
Output Data

98.18	0.0095	82.97	43.26		
-.091	0.080	-0.091	0.080	0.224	-0.096
0.0	90.0	0.0	1.615		
0.0	90.0	0.0	0.0	0.0	0.608
0.0	0.0069	0.0	0.377	0.0	0.370
45.0	45.0	0.0	0.0	0.0	0.239

TABLE 2
Input and Output Data for Square Loop

Input Data

0.002	2.56	-1.0	0.0005				
0.001	1.0	1.0	-1.0	0.0			
1	1	1	1	0	1	4	4
300.	0.0	90.0	0.0	90.0	45.	45.	
1	2						
2	3						
3	4						
4	1						
0.05	-0.05	0.0					
0.05	0.05	0.0					
-0.05	0.05	0.0					
-0.05	-0.05	0.0					
1.0	1.0	1.0					



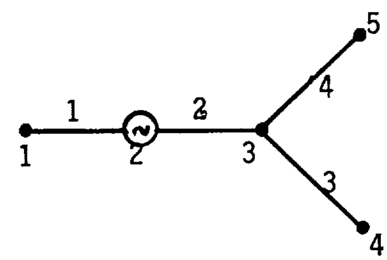
Output Data

73.10	.243E-4	62.94	1609.8		
-.0078	.0027	.0057	.0029	-.0010	-.0056
0.0	90.0	.8066	.0		
0.0	90.0	.0002	.0	.0	.0
.126E-4	0.0	.936E-4	.0	.810E-4	.0
45.0	45.0	.106E-3	.265E-4	.0	.0

TABLE 3
Input and Output Data for Y Antenna

Input Data

0.002	2.56	-1.0	0.0005				
0.001	1.0	1.0	-1.0	0.0			
1	1	1	1	0	2	4	5
300.	0.0	90.0	0.0	90.0	45.	45.	
1	2						
2	3						
3	4						
3	5						
0.0	-0.30	0.0					
0.0	-0.15	0.0					
0.0	0.0	0.0					
0.1	0.1	0.0					
-0.1	0.1	0.0					
1.0	1.0	1.0					



Output Data

97.88	0.013	75.53	-0.572		
-.124	0.081	0.260	-0.064	-0.126	0.070
0.0	90.0	1.535	0.0		
0.0	90.0	0.748	0.0	0.0	0.0
0.0103	0.0	0.487	0.0	0.477	0.0
45.0	45.0	0.360	0.170	0.0	0.0

TABLE 4

Self Impedance of Two-Segment V Dipole Shown in Fig. 2
Radius: a = 0.001λ

ψ	h = 0.10λ	h = 0.15λ	h = 0.20λ	h = 0.25λ
30°	0.59 - j 481	1.4 - j 314	3.1 - j 186	6.1 - j 61
60	2.15 - j 547	5.3 - j 337	11.0 - j 177	21.3 - j 21
90	4.22 - j 572	10.4 - j 340	21.1 - j 163	40.0 + j 9
120	6.31 - j 583	15.3 - j 338	30.9 - j 151	57.7 + j 28
150	7.81 - j 587	18.9 - j 335	37.7 - j 144	69.3 + j 39
180	8.33 - j 589	20.1 - j 335	39.9 - j 142	73.1 + j 42

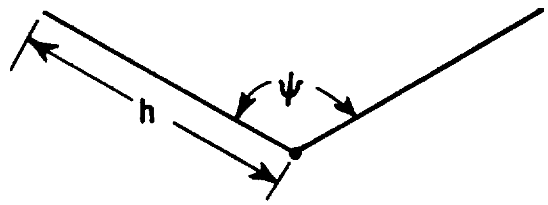


Fig. 2. Symmetric center-fed V dipole.

TABLE 5

Mutual Impedance Between Overlapping V Dipoles in Fig. 3
Radius: $a = 0.001\lambda$

ψ	$h = 0.10\lambda$	$h = 0.15\lambda$	$h = 0.20\lambda$	$h = 0.25\lambda$
60°	-0.96 + j 338	-2.08 + j 285	-3.45 + j 275	- 4.8 + j 298
90	0.19 + j 322	1.03 + j 276	3.57 + j 271	10.1 + j 297
120	3.29 + j 336	8.40 + j 290	17.86 + j 285	35.3 + j 309
150	6.61 + j 346	15.61 + j 299	30.00 + j 291	52.9 + j 309
180	8.01 + j 349	18.47 + j 301	34.35 + j 292	58.2 + j 308

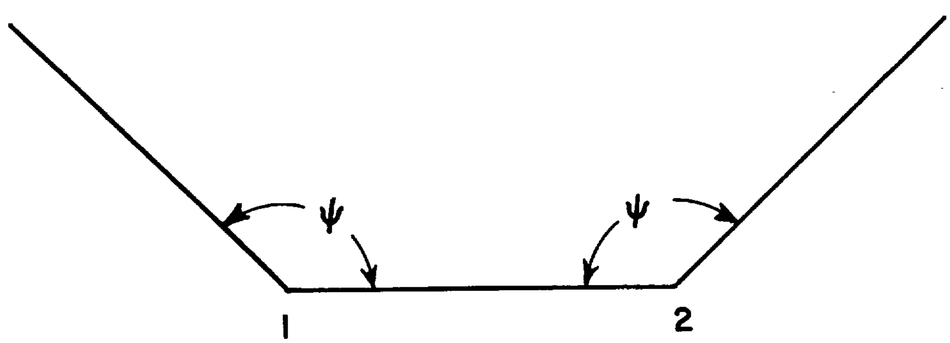


Fig. 3. Overlapping V dipoles share the middle segment.

Tables 6, 7, and 8 list the mutual impedance for other configurations. In all these tables, the data apply to two-segment center-fed sinusoidal dipoles with identical segment lengths h.

TABLE 6
Mutual Impedance Between Overlapping V Dipoles in Fig. 4
Radius: a = 0.001λ

α	h = 0.10λ	h = 0.15λ	h = 0.20λ	h = 0.25λ
30°	6.74 - j 314	16.24 - j 167	32.17 - j 56	58.7 + j 49.6
60	3.16 - j 291	7.68 - j 169	15.47 - j 76	28.8 + j 14.2
90	0.06 - j 278	0.31 - j 172	1.15 - j 92	3.5 - j 12.2
120	-1.01 - j 256	-2.39 - j 168	-4.47 - j 101	-7.6 - j 35.5
150	-0.48 - j 207	-1.20 - j 146	-2.40 - j 98	-4.5 - j 50.7

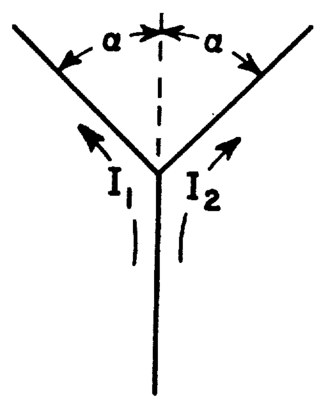


Fig. 4. Overlapping V dipoles share the bottom segment in a planar Y configuration.

TABLE 7
Mutual Impedance Between the Coplanar-Skew Linear Dipoles in Fig. 5
Displacement: $d = \lambda$

θ	h = 0.10λ	h = 0.15λ	h = 0.20λ	h = 0.25λ
0°	0.337 + j 1.952	0.880 + j 4.759	1.932 + j 9.547	4.011 + j 17.7
15	0.322 + j 1.884	0.831 + j 4.585	1.799 + j 9.180	3.671 + j 17.0
30	0.281 + j 1.684	0.700 + j 4.082	1.448 + j 8.128	2.800 + j 15.0
45	0.220 + j 1.369	0.521 + j 3.301	1.000 + j 6.519	1.745 + j 11.9
60	0.149 + j 0.964	0.333 + j 2.310	0.579 + j 4.524	0.860 + j 8.1
75	0.075 + j 0.497	0.159 + j 1.187	0.252 + j 2.308	0.305 + j 4.1
90	0.0 + j 0.0	0.0 + j 0.0	0.0 + j 0.0	0.0 + j 0.0

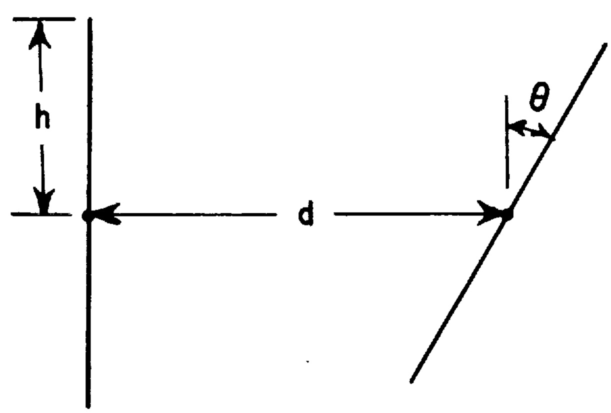


Fig. 5. Center-fed coplanar-skew linear dipoles.

TABLE 8
Mutual Impedance Between the Nonplanar-Skew Linear Dipoles in Fig. 6
Displacement: $d = \lambda$

ϕ	$h = 0.10\lambda$	$h = 0.15\lambda$	$h = 0.20\lambda$	$h = 0.25\lambda$
0°	0.337 + j 1.952	0.880 + j 4.759	1.932 + j 9.547	4.011 + j 17.74
15	0.326 + j 1.886	0.850 + j 4.596	1.867 + j 9.222	3.877 + j 17.14
30	0.292 + j 1.691	0.762 + j 4.121	1.675 + j 8.269	3.482 + j 15.37
45	0.238 + j 1.380	0.622 + j 3.365	1.369 + j 6.752	2.850 + j 12.55
60	0.169 + j 0.976	0.440 + j 2.380	0.969 + j 4.775	2.020 + j 8.88
75	0.087 + j 0.505	0.228 + j 1.232	0.502 + j 2.472	1.047 + j 4.60
90	0.0 + j 0.0	0.0 + j 0.0	0.0 + j 0.0	0.0 + j 0.0

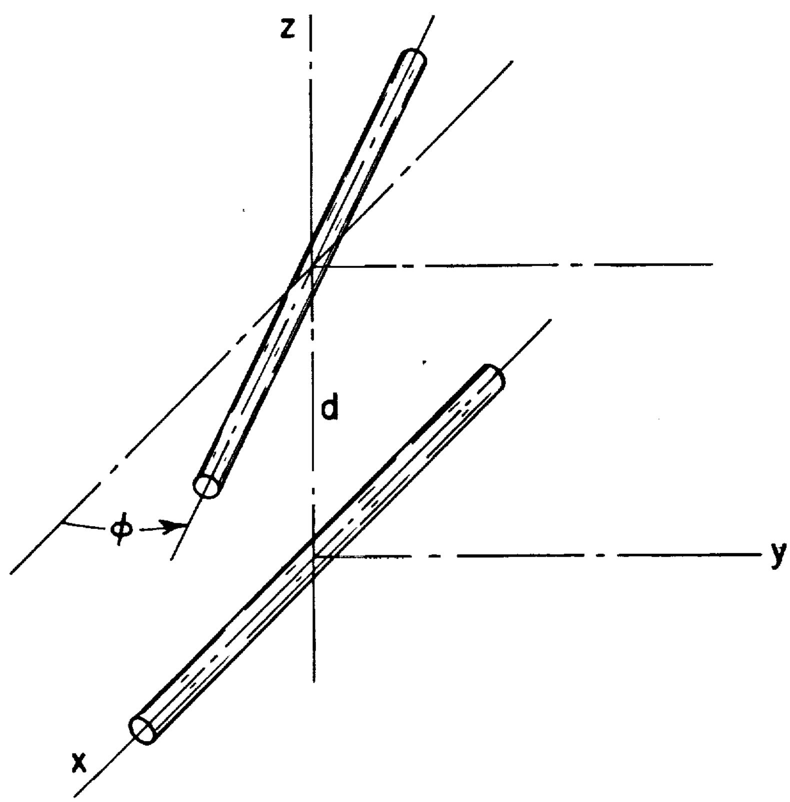


Fig. 6. Center-fed nonplanar-skew linear dipoles.

III. SUMMARY

This report presents the sinusoidal-reaction computer program for thin-wire antennas and scatterers, instructions for the user, typical input and output data and mutual-impedance tables for sinusoidal dipoles. Appendices list the computer subroutines and explain their functions.

REFERENCES

1. Richmond, J.H., "Radiation and scattering by thin-wire structures in the complex frequency domain," Report 2902-10, July, 1973, The Ohio State University ElectroScience Laboratory, Department of Electrical Engineering; prepared under Grant NGL 36-008-138 for National Aeronautics and Space Administration, Langley Research Center. (Available as NASA CR-2396, 1974.)

2. Imbriale, W.A., and Ingerson, P.G., "On numerical convergence of moment solutions of moderately thick wire antennas using sinusoidal basis functions," IEEE Trans., Vol. AP-21, May 1973, pp. 363-366.

3. Abramowitz, M., and Stegun, I.A., "Handbook of mathematical functions with formulas, graphs, and mathematical tables," National Bureau of Standards, Applied Mathematics Series AMS-55, 1964, Chapter 5.

4. Faddeev, D.K., and Faddeeva, V.N., Computational Methods of Linear Algebra, W. H. Freeman and Company, San Francisco, 1963, pp. 144-147.

APPENDIX 1. Subroutine SORT

Subroutine SORT, listed in Fig. 7, defines a set of dipole mode currents on the wire structure. The input data IA, IB, NM, NP, ICJ and INM have been defined already. The output data are defined as follows:

N	total number of dipole modes
I1(I)	endpoint of dipole I
I2(I)	terminal point of dipole I
I3(I)	endpoint of dipole I
JA(I)	first segment of dipole I
JB(I)	second segment of dipole I
MD(J,K)	list of dipoles sharing segment J
ND(J)	total number of dipoles sharing segment J
MAX,MIN	extreme values of ND(J)

At completion of the DO LOOP ending with statement 20, NJK denotes the number of segments intersecting at point K, and JSP is a list of these segments. In the DO LOOP ending with statement 22, the computer sets up the appropriate number MOD of dipoles modes with terminals at poink K.

APPENDIX 2. Subroutine SGANT

Subroutine SGANT, listed in Fig. 8, calculates the mutual impedances Z_{ij} and stores them in C(K). The input data for SGANT have been defined already. The output data are defined as follows:

C(K)	open-circuit impedance matrix
CGD(J)	cosh γd for segment J
SGD(J)	sinh γd for segment J
D(J)	length of segment J
ZS	surface impedance of the wire

The surface impedance is calculated just above statement 12. B01 denotes J_0/J_1 where J_0 and J_1 are the Bessel functions of order zero and one with complex argument ZARG. It is assumed that all the wire segments have the same radius, conductivity and surface impedance.

In the DO LOOP ending with statement 20, SGANT calculates the segment lengths D(J). DMIN and DMAX denote the lengths of the shortest and longest segments. If the wire radius or the segment lengths are clearly beyond the range of thin-wire theory, N is set to zero at statement 25 followed by RETURN to the main program to abort the calculation.

At statement 30, the program selects a segment K, and a few statements below this it selects another segment L. K is a segment of test dipole I, and L is a segment of expansion mode J. The mutual impedance between segments K and L is obtained by calling subroutine GGS or GGMM.

```
      SUBROUTINE SORT(IA,IB,I1,I2,I3,JA,JB,MD,ND,NM,NP,N,MAX,MIN
     2,ICJ,INM)
      DIMENSION JSP(20)
      DIMENSION I1(1),I2(1),I3(1),JA(1),JB(1)
      DIMENSION IA(1),IB(1),ND(1),MD(INM,4)
      I=0
      DO 24 K=1,NP
      NJK=0
      DO 20 J=1,NM
      IND=(IA(J)-K)*(IB(J)-K)
      IF(IND.NE.0)GO TO 20
      NJK=NJK+1
      JSP(NJK)=J
   20 CONTINUE
      MOD=NJK-1
      IF(MOD.LE.0)GO TO 24
      DO 22 IMD=1,MOD
      I=I+1
      IF(I.GT.ICJ)GO TO 22
      IPD=IMD+1
      JAI=JSP(IMD)
      JA(I)=JAI
      JBI=JSP(IPD)
      JB(I)=JBI
      I1(I)=IA(JAI)
      IF(IA(JAI).EQ.K)I1(I)=IB(JAI)
      I2(I)=K
      I3(I)=IA(JBI)
      IF(IA(JBI).EQ.K)I3(I)=IB(JBI)
   22 CONTINUE
   24 CONTINUE
      N=I
      DO 30 J=1,NM
      ND(J)=0
      DO 30 K=1,4
   30 MD(J,K)=0
      III=N
      IF(N.GT.ICJ)III=ICJ
      DO 40 I=1,III
      J=JA(I)
      DO 38 L=1,2
      ND(J)=ND(J)+1
      K=1
      M=0
   32 MJK=MD(J,K)
      IF(MJK.NE.0)GO TO 34
      M=1
      MD(J,K)=I
   34 K=K+1
      IF(K.GT.4)GO TO 38
      IF(M.EQ.0)GO TO 32
   38 J=JB(I)
   40 CONTINUE
      MIN=100
      MAX=0
      DO 46 J=1,NM
      NDJ=ND(J)
      IF(NDJ.GT.MAX)MAX=NDJ
   46 IF(NDJ.LT.MIN)MIN=NDJ
      RETURN
      END
```

Fig. 7. Subroutine SORT

```
      SUBROUTINE SGANT(IA,IB,INM,INT,ISC,I1,I2,I3,JA,JB,MD,N,ND,NM,NP
     2,AM,BM,C,CGD,CMM,D,EP2,EP3,ETA,FHZ,GAM,SGD,X,Y,Z,ZLD,ZS)
      COMPLEX ZG,ZH,ZS,EGD,GD,CGDS,SGDS,SGDT,B01
      COMPLEX P11,P12,P21,P22,Q11,Q12,Q21,Q22,EP2,EP,ETA,GAM,EP3
      COMPLEX EPSILA,CWEA,BETA,ZARG
      COMPLEX P(2,2),Q(2,2),CGD(1),SGD(1),C(1),ZLD(1)
      DIMENSION X(1),Y(1),Z(1),D(1),IA(1),IB(1),MD(INM,4)
      DIMENSION I1(1),I2(1),I3(1),JA(1),JB(1),ND(1),ISC(1)
      DATA E0,TP,U0/8.854E-12,6.28318,1.2566E-6/
    2 FORMAT(3X,'AM = ',E10.3,3X,'DMAX = ',E10.3,3X,'DMIN = ',E10.3)
      EP=EP3
      ICC=(N*N+N)/2
      DO 10 I=1,ICC
   10 C(I)=(.0,.0)
      ZS=(.0,.0)
      IF(CMM.LE.0.)GO TO 12
      OMEGA=TP*FHZ
      EPSILA=CMPLX(E0,-CMM*1.E6/OMEGA)
      CWEA=(.0,1.)*OMEGA*EPSILA
      BETA=OMEGA*SQRT(U0)*CSQRT(EPSILA-EP)
      ZARG=BETA*AM
      CALL CBES(ZARG,B01)
      ZS=BETA*B01/CWEA
   12 ZH=ZS/(TP*AM*GAM)
      DMIN=1.E30
      DMAX=.0
      DO 20 J=1,NM
      K=IA(J)
      L=IB(J)
      D(J)=SQRT((X(K)-X(L))**2+(Y(K)-Y(L))**2+(Z(K)-Z(L))**2)
      IF(D(J).LT.DMIN)DMIN=D(J)
      IF(D(J).GT.DMAX)DMAX=D(J)
      EGD=CEXP(GAM*D(J))
      CGD(J)=(EGD+1./EGD)/2.
   20 SGD(J)=(EGD-1./EGD)/2.
      IF(DMIN.LT.2.*AM)GO TO 25
      IF(CABS(GAM*AM).GT.0.06)GO TO 25
      IF(CABS(GAM*DMAX).GT.3.)GO TO 25
      IF(AM.GT.0.)GO TO 30
   25 N=0
      WRITE(6,2)AM,DMAX,DMIN
      RETURN
   30 DO 200 K=1,NM
      NDK=ND(K)
      KA=IA(K)
      KB=IB(K)
      DK=D(K)
      CGDS=CGD(K)
      SGDS=SGD(K)
      DO 200 L=1,NM
      NDL=ND(L)
      LA=IA(L)
      LB=IB(L)
      DL=D(L)
      SGDT=SGD(L)
      NIL=0
      DO 200 II=1,NDK
      I=MD(K,II)
      MM=(I-1)*N-(I*I-I)/2
      FI=1.
      IF(KB.EQ.I2(I))GO TO 36
      IF(KB.EQ.I1(I))FI=-1.
```

Fig. 8a. Subroutine SGANT

```
      IS=1
      GO TO 40
   36 IF(KA.EQ.I3(I))FI=-1.
      IS=2
   40 DO 200 JJ=1,NDL
      J=MD(L,JJ)
      MMM=MM+J
      IF(I.GT.J)GO TO 200
      FJ=1.
      IF(LB.EQ.I2(J))GO TO 46
      IF(LB.EQ.I1(J))FJ=-1.
      JS=1
      GO TO 50
   46 IF(LA.EQ.I3(J))FJ=-1.
      JS=2
   50 IF(NIL.NE.0)GO TO 168
      NIL=1
      IF(K.EQ.L)GO TO 120
      IND=(LA-KA)*(LB-KA)*(LA-KB)*(LB-KB)
      IF(IND.EQ.0)GO TO 80
C     SEGMENTS K AND L SHARE NO POINTS
      CALL GGS(X(KA),Y(KA),Z(KA),X(KB),Y(KB),Z(KB),X(LA),Y(LA),Z(LA)
     2,X(LB),Y(LB),Z(LB),AM,DK,CGDS,SGDS,DL,SGDT,INT,ETA,GAM
     3,P(1,1),P(1,2),P(2,1),P(2,2))
      GO TO 168
C     SEGMENTS K AND L SHARE ONE POINT (THEY INTERSECT)
   80 KG=0
      JM=KB
      JC=KA
      KF=1
      IND=(KB-LA)*(KB-LB)
      IF(IND.NE.0)GO TO 82
      JC=KB
      KF=-1
      JM=KA
      KG=3
   82 LG=3
      JP=LA
      LF=-1
      IF(LB.EQ.JC)GO TO 83
      JP=LB
      LF=1
      LG=0
   83 SGN=KF*LF
      CPSI=((X(JP)-X(JC))*(X(JM)-X(JC))+(Y(JP)-Y(JC))*(Y(JM)-Y(JC))
     2+(Z(JP)-Z(JC))*(Z(JM)-Z(JC)))/(DK*DL)
      CALL GGMM(.0,DK,.0,DL,AM,CGDS,SGDS,SGDT,CPSI,ETA,GAM
     2,Q(1,1),Q(1,2),Q(2,1),Q(2,2))
      DO 98 KK=1,2
      KP=IABS(KK-KG)
      DO 98 LL=1,2
      LP=IABS(LL-LG)
      P(KP,LP)=SGN*Q(KK,LL)
   98 CONTINUE
      GO TO 168
C     K=L  (SELF REACTION OF SEGMENT K)
  120 Q11=(.0,.0)
      Q12=(.0,.0)
      IF(CMM.LE.0.)GO TO 150
      GD=GAM*DK
      ZG=ZH/(SGDS**2)
      Q11=ZG*(SGDS*CGDS-GD)/2.
```

Fig. 8b. Subroutine SGANT

```
      Q12=ZG*(GD*CGDS-SGDS)/2.
  150 ISCK=ISC(K)
      P11=(.0,.0)
      P12=(.0,.0)
      IF(ISCK.EQ.0)GO TO 155
      IF(BM.LE.AM)GO TO 155
      CALL        DSHELL(AM,BM,DK,CGDS,SGDS,EP2,EP,ETA,GAM,P11,P12)
  155 Q11=P11+Q11
      Q12=P12+Q12
      CALL GGMM(.0,DK,.0,DK,AM,CGDS,SGDS,SGDS,1.
     2,ETA,GAM,P11,P12,P21,P22)
      Q11=P11+Q11
      Q12=P12+Q12
      P(1,1)=Q11
      P(1,2)=Q12
      P(2,1)=Q12
      P(2,2)=Q11
      IF(KA.NE.LA)GO TO 160
      GO TO 168
  160 P(1,1)=-Q12
      P(1,2)=-Q11
      P(2,1)=-Q11
      P(2,2)=-Q12
  168 C(MMM)=C(MMM)+FI*FJ*P(IS,JS)
  200 CONTINUE
      DO 220 I=1,N
      IJ=(I-1)*N-(I*I-1)/2+I
      J1=JA(I)
      IF(I2(I).EQ.IB(J1))J1=J1+NM
      J2=JB(I)
      IF(I2(I).EQ.IB(J2))J2=J2+NM
  220 C(IJ)=C(IJ)+ZLD(J1)+ZLD(J2)
      RETURN
      END
```

Fig. 8c. Subroutine SGANT

In statement 168, this impedance is lumped into C(MMM). The mutual impedance Z_{ij} between dipoles I and J is the sum of four segment-segment impedances.

In SGANT, segment K has endpoints KA and KB, and segment L has endpoints LA and LB. It is convenient to think of KA and KB as points 1 and 2 on segment K, and LA and LB as points 1 and 2 on L. Now we define four segment-segment impedances P(IS,JS). The first subscript IS refers to the terminal point on segment K, and the second subscript JS refers to the terminal point on L. Thus IS = 1 or 2 if dipole I has its terminal point I2(I) at KA (point 1) or KB (point 2), respectively. Similarly, JS = 1 or 2 if mode J has its terminal point I2(J) at LA or LB. The impedances P(IS,JS) are defined with the following reference directions for current flow: from point 1 toward point 2 on each segment. If dipole I has this same reference direction on segment K, we set FI = 1; otherwise FI = -1. Similarly FJ = 1 or -1 in accordance with the reference direction for mode J on segment L. In statement 168, P(IS,JS) is multiplied by FI and FJ before its contribution is added to Z_{ij}.

Subroutine GGMM calculates the impedances Q(KK,LL) which are like the P(IS,JS) but have different conventions for reference directions and subscript meaning. The transformation from the Q impedances to the P impedances is accomplished in the DO LOOP ending with statement 98.

If the wire has finite conductivity, the appropriate modification is applied to the impedance matrix just above statement 150. (See Eqs. 27 through 29 in Reference 1.) The terms arising from the dielectric shell on an insulated segment are obtained from subroutine DSHELL just above statement 155. Finally, the lumped loads ZLD are added to the diagonal elements of the impedance matrix in statement 220.

The impedance matrix could be calculated in a different order as follows. Select modes I and J, calculate ZIJ, and then increment I or J. Instead, SGANT selects segments K and L, calculates ZKL, adds ZKL to all the appropriate elements ZIJ, and then increments K or L. This minimizes the calls to GGS and GGMM and presumably improves the computational efficiency.

K is a segment of test dipole I, and L is a segment of expansion mode J. When the segment numbers K and L are equal, SGANT calls GGMM to obtain the mutual impedance between two filamentary electric monopoles. These monopoles are parallel and have the same length. Monopole K is positioned on the axis of the wire segment, and monopole L is on the surface of the same wire segment. Thus, the displacement is equal to the wire radius. The two monopoles are side-by-side with no stagger.

When segments K and L intersect, SGANT again calls GGMM for the mutual impedance between the two filamentary monopoles. Monopole K is situated on the axis of wire segment K, and monopole L is on the surface of wire segment L. The axes of segments K and L define a plane P, and monopole K lies in this plane. Monopole L is parallel with plane P and is displaced from it by a distance equal to the wire radius.

APPENDIX 3. Subroutine CBES

Subroutine CBES, listed in Fig. 9, calculates the quantity B01 = $J_0(z)/J_1(z)$ where z is complex and J_0 and J_1 denote the Bessel functions of order zero and one.

APPENDIX 4. Subroutine DSHELL

Subroutine DSHELL, listed in Fig. 10, calculates the mutual impedance term contributed by the dielectric insulation on the surface of a thin wire. This subroutine uses Eq. 35 of Reference 1.

APPENDIX 5. Subroutine GGS

Subroutine GGS, listed in Fig. 11, calculates the mutual impedance between two filamentary monopoles with sinusoidal current distributions. (The dipole-dipole mutual impedance in Eq. 20 of Reference 1 is the sum of four monopole-monopole mutual impedances.) The endpoints of the axial test monopole s are (XA,YA,ZA) and (XB,YB,ZB), and the endpoints of the expansion monopole t are (X1,Y1,Z1) and (X2,Y2,Z2). DS and DT denote the lengths of monopoles s and t, respectively. CAS, CBS and CGS are the direction cosines of monopole s, and CA, CB and CG are the direction cosines of monopole t.

If INT = 0, GGS calls GGMM for the closed-form impedance calculations. Otherwise GGS calculates the mutual impedance via Simpson's-rule integration with the following number of sample points: IP = INT + 1. If the monopoles are parallel with small displacement, GGS calls GGMM to avoid the difficulties of numerical integration.

For the fields of the test monopole, GGS uses Eqs. 75 and 76 of Reference 1. The current distribution on the expansion monopole is given by Eq. 74 of Reference 1. With an origin at (X1,Y1,Z1), the coordinate T measures distance along the expansion monopole. Thus T is the integration variable.

Let the coordinate s measure distance along the test monopole with origin at (XA,YA,ZA). From any point T on monopole t, construct a line to the test monopole such that the line is perpendicular to the test monopole. SZ denotes the s coordinate of the intersection of this line with the test monopole. The length of the line is the radial coordinate ρ, and RS denotes ρ^2. R1 and R2 are the distances from (XA,YA,ZA) and (XB,YB,ZB) to the point T. C1 is the current at T for the mode with terminals at (X1,Y1,Z1), and C2 is the current at T for the other mode with terminals at (X2,Y2,Z2). C denotes the Simpson's-rule weighting coefficient.

```
      SUBROUTINE CBES(Z,B01)
      COMPLEX ARG,CC,CS,EX
      COMPLEX B01,Z,TERMJ,TERMN,MZ24,JN(2)
      DATA PI/3.14159/
      IF(CABS( Z ).GE.12.0) GO TO10
      FACTOR=0.0
      TERMN=(0.,0.)
      MZ24=-0.25*Z*Z
      TERMJ=(1.0,0.0)
      DO 1 NP=1,2
      N=NP-1
      JN(NP)=TERMJ
      M=0
    2 M=M+1
      TERMJ=TERMJ*MZ24/FLOAT(M*(N+M))
      JN(NP)=JN(NP)+TERMJ
      IF(NP.NE.1) GO TO 3
      FACTOR=FACTOR+1.0/FLOAT(M)
      TERMN=TERMN+TERMJ*FACTOR
    3 ERROR=CABS(TERMJ)
      IF(ERROR.GT.1.0E-10) GO TO 2
    1 TERMJ=0.5*Z
      B01=JN(1)/JN(2)
      RETURN
 10   Y=AIMAG(Z)
      IF(ABS(Y).GT.20.)GO TO 20
      ARG=(.0,1.)*Z
      EX=CEXP(ARG)
      CC=EX+1./EX
      CS=(.0,-1.)*(EX-1./EX)
      B01=(CS+CC)/(CS-CC)
      RETURN
 20   B01=(.0,-1.)
      IF(Y.LT.0.)B01=(.0,1.)
      RETURN
      END
```

Fig. 9. Subroutine CBES

```
SUBROUTINE DSHELL(AM,BM,DK,CGDS,SGDS,EP2,EP,ETA,GAM,P11,P12)
COMPLEX CGDS,SGDS,EP2,EP,ETA,GAM,P11,P12,GD,CST
DATA PI/3.14159/
GD=GAM*DK
CST=(EP2-EP )*ETA*ALOG(BM/AM)/(4.*PI*EP2*SGDS*SGDS)
P11=-CST*(GD+SGDS*CGDS)
P12=CST*(GD*CGDS+SGDS)
RETURN
END
```

Fig. 10. Subroutine DSHELL.

```
      SUBROUTINE GGS(XA,YA,ZA,XB,YB,ZB,X1,Y1,Z1,X2,Y2,Z2,AM
     2,DS,CGDS,SGDS,DT,SGDT,INT,ETA,GAM,P11,P12,P21,P22)
      COMPLEX P11,P12,P21,P22,EJA,EJB,EJ1,EJ2,ETA,GAM,C1,C2,CST
      COMPLEX EGD,CGDS,SGDS,SGDT,ER1,ER2,ET1,ET2
      DATA FP/12.56637/
      CA=(X2-X1)/DT
      CB=(Y2-Y1)/DT
      CG=(Z2-Z1)/DT
      CAS=(XB-XA)/DS
      CBS=(YB-YA)/DS
      CGS=(ZB-ZA)/DS
      CC=CA*CAS+CB*CBS+CG*CGS
      IF(ABS(CC).GT..997)GO TO 200
   20 SZ=(X1-XA)*CAS+(Y1-YA)*CBS+(Z1-ZA)*CGS
      IF(INT.LE.0)GO TO 300
      INS=2*(INT/2)
      IF(INS.LT.2)INS=2
      IP=INS+1
      DELT=DT/INS
      T=.0
      DSZ=CC*DELT
      P11=(.0,.0)
      P12=(.0,.0)
      P21=(.0,.0)
      P22=(.0,.0)
      AMS=AM*AM
      SGN=-1.
      DO 100 IN=1,IP
      ZZ1=SZ
      ZZ2=SZ-DS
      XXZ=X1+T*CA-XA-SZ*CAS
      YYZ=Y1+T*CB-YA-SZ*CBS
      ZZZ=Z1+T*CG-ZA-SZ*CGS
      RS=XXZ**2+YYZ**2+ZZZ**2
      R1=SQRT(RS+ZZ1**2)
      EJA=CEXP(-GAM*R1)
      EJ1=EJA/R1
      R2=SQRT(RS+ZZ2**2)
      EJB=CEXP(-GAM*R2)
      EJ2=EJB/R2
      ER1=EJA*SGDS+ZZ1*EJ1*CGDS-ZZ2*EJ2
      ER2=-EJB*SGDS+ZZ2*EJ2*CGDS-ZZ1*EJ1
      FAC=.0
      IF(RS.GT.AMS)FAC=(CA*XXZ+CB*YYZ+CG*ZZZ)/RS
      ET1=CC*(EJ2-EJ1*CGDS)+FAC*ER1
      ET2=CC*(EJ1-EJ2*CGDS)+FAC*ER2
      C=3.+SGN
      IF(IN.EQ.1 .OR. IN.EQ.IP)C=1.
      EGD=CEXP(GAM*(DT-T))
      C1=C*(EGD-1./EGD)/2.
      EGD=CEXP(GAM*T)
      C2=C*(EGD-1./EGD)/2.
      P11=P11+ET1*C1
      P12=P12+ET1*C2
      P21=P21+ET2*C1
      P22=P22+ET2*C2
      T=T+DELT
      SZ=SZ+DSZ
  100 SGN=-SGN
      CST=-ETA*DELT/(3.*FP*SGDS*SGDT)
      P11=CST*P11
      P12=CST*P12
```

Fig. 11a. Subroutine GGS

```
      P21=CST*P21
      P22=CST*P22
      RETURN
200   SZ1=(X1-XA)*CAS+(Y1-YA)*CBS+(Z1-ZA)*CGS
      RH1=SQRT((X1-XA-SZ1*CAS)**2+(Y1-YA-SZ1*CBS)**2+(Z1-ZA-SZ1*CGS)**2)
      SZ2=SZ1+DT*CC
      RH2=SQRT((X2-XA-SZ2*CAS)**2+(Y2-YA-SZ2*CBS)**2+(Z2-ZA-SZ2*CGS)**2)
      DDD=(RH1+RH2)/2.
      IF(DDD.GT.20.*AM .AND. INT.GT.0)GO TO 20
      IF(DDD.LT.AM)DDD=AM
      CALL GGMM(.0,DS,SZ1,SZ2,DDD,CGDS,SGDS,SGDT,1.
     2,ETA,GAM,P11,P12,P21,P22)
      RETURN
300   SS=SQRT(1.-CC*CC)
      CAD=(CGS*CB-CBS*CG)/SS
      CBD=(CAS*CG-CGS*CA)/SS
      CGD=(CBS*CA-CAS*CB)/SS
      DK=(X1-XA)*CAD+(Y1-YA)*CBD+(Z1-ZA)*CGD
      DK=ABS(DK)
      IF(DK.LT.AM)DK=AM
      XZ=XA+SZ*CAS
      YZ=YA+SZ*CBS
      ZZ=ZA+SZ*CGS
      XP1=X1-DK*CAD
      YP1=Y1-DK*CBD
      ZP1=Z1-DK*CGD
      CAP=CBS*CGD-CGS*CBD
      CBP=CGS*CAD-CAS*CGD
      CGP=CAS*CBD-CBS*CAD
      P1=CAP*(XP1-XZ)+CBP*(YP1-YZ)+CGP*(ZP1-ZZ)
      T1=P1/SS
      S1=T1*CC-SZ
      CALL GGMM(S1,S1+DS,T1,T1+DT,DK,CGDS,SGDS,SGDT,CC,ETA,GAM
     2,P11,P12,P21,P22)
      RETURN
      END
```

Fig. 11b. Subroutine GGS

Below statement 300, GGS performs some analytic geometry in preparation for calling GGMM. The remaining part of this Appendix concerns this last part of subroutine GGS.

Let $\hat{s}$ denote a unit vector in the direction from (XA,YA,ZA) toward (XB,YB,ZB). Also let $\hat{t}$ denote a unit vector from (X1,Y1,Z1) toward (X2,Y2,Z2). Then $\hat{s} \cdot \hat{t} = \cos\theta =$ CC where θ is the angle formed by the axes of the two monopoles. Let monopole s lie in one plane P_s and monopole t lie in another parallel plane P_t. CAD, CBD and CGD are the direction cosines of the unit vector $\hat{d} = \hat{t} \times \hat{s} / \sin\theta$ which is perpendicular to both planes. To obtain the distance DK between the two planes, we construct a vector $\underline{R}_{11}$ from (XA,YA,ZA) to (X1,Y1,Z1) and take DK = $\underline{R}_{11} \cdot \hat{d}$.

Construct a line from (X1,Y1,Z1) to the test monopole, such that the line is perpendicular to the test monopole. SZ denotes the s coordinate of the intersection of this line with the test monopole, and the cartesian coordinates of this intersection are XZ, YZ and ZZ. The direction cosines of $\hat{s} \times \hat{d}$ are CAP, CBP and CGP.

From the point (X1,Y1,Z1) in plane P_t, construct a perpendicular line to the point (XP1,YP1,ZP1) in the plane P_s. This line is parallel with $\hat{d}$ and has length DK. Let $\underline{R}$ represent a vector from (XZ,YZ,ZZ) to (XP1,YP1,ZP1). P1 denotes $\underline{R} \cdot (\hat{s} \times \hat{d})$. S1 and T1 are defined in the next Appendix.

APPENDIX 6. Subroutine GGMM

Subroutine GGMM calculates the mutual impedance between two filamentary monopoles with sinusoidal current distributions. The dipole-dipole mutual impedance in Eq. 20 of Reference 1 is the sum of four monopole-monopole mutual impedances. The monopole impedances are calculated by GGS with Simpson's rule or by GGMM with closed-form expressions in terms of exponential integrals.

To explain the input data for GGMM, reference is made to Fig. 12. Subroutine GGMM is listed in Fig. 13. If the monopoles are parallel, let the z axis be parallel with both monopoles. The coordinate origin may be selected arbitrarily. S1 and S2 denote the z coordinates of the endpoints of the test monopole, T1 and T2 are the z coordinates of the endpoints of the expansion monopole, and D is the perpendicular distance (displacement) between the monopoles. The mutual impedance of parallel monopoles is calculated in the last part of GGMM below statement 110.

For skew monopoles, let the test monopole s lie in the xy plane and the expansion monopole t in the plane z = D. (D is the perpendicular distance between the parallel planes.) If the monopoles are viewed along a line of sight parallel with the z axis as in Fig. 12, the extended axes of the two monopoles will appear to intersect at a point on the xy plane. Let s measure the distance along the axis of

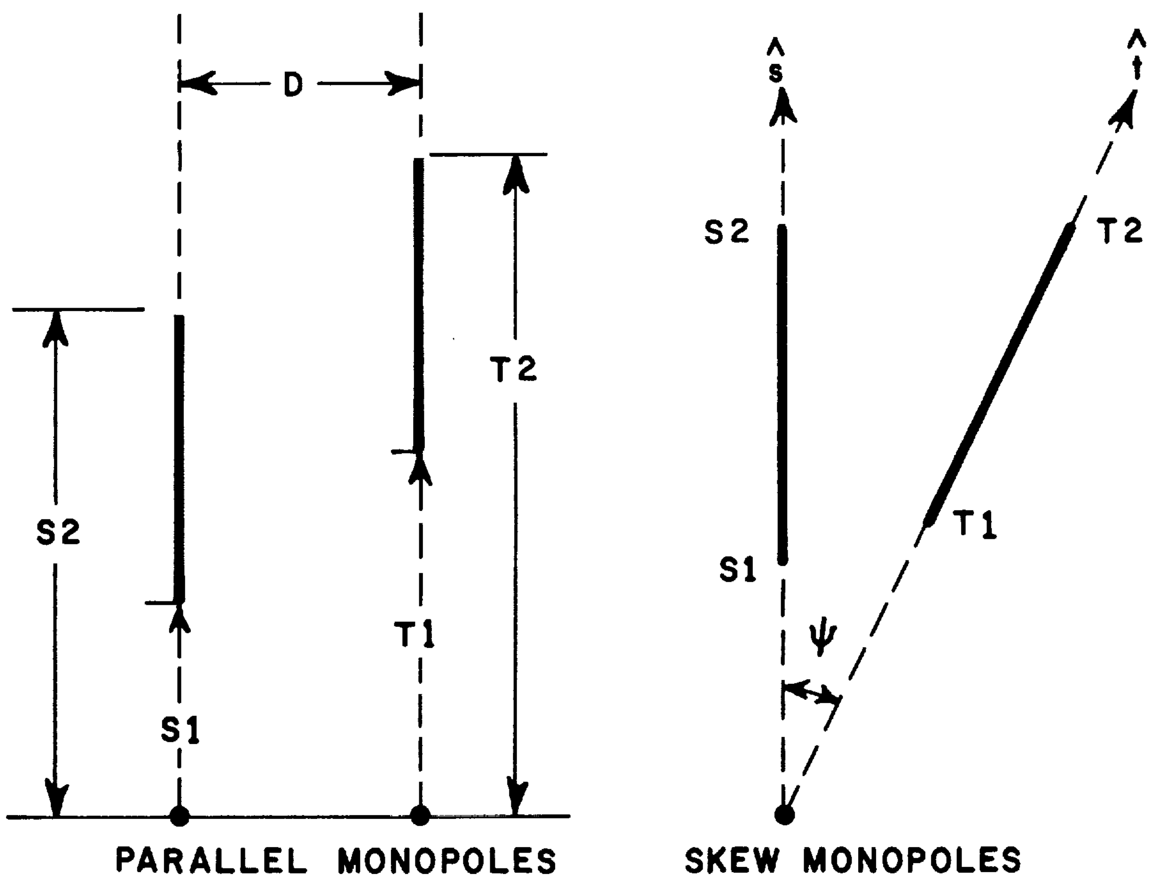


Fig. 12. Coordinates for parallel and skew monopoles in subroutine GGMM.

```
      SUBROUTINE GGMM(S1,S2,T1,T2,D,CGDS,SGD1,SGD2,CPSI,ETA,GAM
     2,P11,P12,P21,P22)
      DOUBLE PRECISION R1,R2,DPQ,SIS,TS1,TS2,ST1,ST2,CD,BD,CPSS,SK
     2,TL1,TL2,TD1,TD2,SDI,DPSI,DD,ZD
      COMPLEX CGDS,SGDS,SGDT,SGD1,SGD2,ETA,GAM,P11,P12,P21,P22
      COMPLEX CST,EB,EC,EK,EL,EKL,EGZI,ES1,ES2,ET1,ET2,EXPA,EXPB
      COMPLEX E(2,2),F(2,2)
      COMPLEX EGZ(2,2),GM(2),GP(2)
      DATA PI/3.14159/
      DSQ=D*D
      SGDS=SGD1
      IF(S2.LT.S1)SGDS=-SGD1
      SGDT=SGD2
      IF(T2.LT.T1)SGDT=-SGD2
      IF(ABS(CPSI).GT..997)GO TO 110
      ES1=CEXP(GAM*S1)
      ES2=CEXP(GAM*S2)
      ET1=CEXP(GAM*T1)
      ET2=CEXP(GAM*T2)
      DD=D
      DPSI=CPSI
      TD1=T1
      TD2=T2
      CPSS=DPSI*DPSI
      CD=DD/DSQRT(1.D0-CPSS)
      C=CD
      BD=CD*DPSI
      B=BD
      EB=CEXP(GAM*CMPLX(.0,B))
      EC=CEXP(GAM*CMPLX(.0,C))
      DO 10 K=1,2
      DO 10 L=1,2
   10 E(K,L)=(.0,.0)
      TS1=TD1*TD1
      TS2=TD2*TD2
      DPQ=DD*DD
      SI=S1
      DO 100 I=1,2
      FI=(-1)**I
      SDI=SI
      SIS=SDI*SDI
      ST1=2.*SDI*TD1*DPSI
      ST2=2.*SDI*TD2*DPSI
      R1=DSQRT(DPQ+SIS+TS1-ST1)
      R2=DSQRT(DPQ+SIS+TS2-ST2)
      EK=EB
      DO 50 K=1,2
      FK=(-1)**K
      SK=FK*SDI
      EL=EC
      DO 40 L=1,2
      FL=(-1)**L
      EKL=EK*EL
      XX=FK*BD+FL*CD
      TL1=FL*TD1
      TL2=FL*TD2
      RR1=R1+SK+TL1
      RR2=R2+SK+TL2
      CALL EXPJ(GAM*CMPLX(RR1,-XX),GAM*CMPLX(RR2,-XX),EXPA)
      CALL EXPJ(GAM*CMPLX(RR1,XX),GAM*CMPLX(RR2,XX),EXPB)
      E(K,L)=E(K,L)+FI*(EXPA*EKL+EXPB/EKL)
   40 EL=1./EC
```

Fig. 13a. Subroutine GGMM

```
   50 EK=1./EB
      ZD=SDI*DPSI
      ZC=ZD
      EGZI=CEXP(GAM*ZC)
      RR1=R1+ZD-TD1
      RR2=R2+ZD-TD2
      CALL EXPJ(GAM*RR1,GAM*RR2,EXPB)
      RR1=R1-ZD+TD1
      RR2=R2-ZD+TD2
      CALL EXPJ(GAM*RR1,GAM*RR2,EXPA)
      F(I,1)=2.*SGDS*EXPA/EGZI
      F(I,2)=2.*SGDS*EXPB*EGZI
  100 SI=S2
      CST=ETA/(16.*PI*SGDS*SGDT)
      P11=CST*(( F(1,1)+E(2,2)*ES2-E(1,2)/ES2)*ET2
     A         +(-F(1,2)-E(2,1)*ES2+E(1,1)/ES2)/ET2)
      P12=CST*((-F(1,1)-E(2,2)*ES2+E(1,2)/ES2)*ET1
     B         +( F(1,2)+E(2,1)*ES2-E(1,1)/ES2)/ET1)
      P21=CST*((-F(2,1)-E(2,2)*ES1+E(1,2)/ES1)*ET2
     C         +( F(2,2)+E(2,1)*ES1-E(1,1)/ES1)/ET2)
      P22=CST*(( F(2,1)+E(2,2)*ES1-E(1,2)/ES1)*ET1
     D         +(-F(2,2)-E(2,1)*ES1+E(1,1)/ES1)/ET1)
      RETURN
  110 IF(CPSI.LT.0.)GO TO 120
      TA=T1
      TB=T2
      GO TO 130
  120 TA=-T1
      TB=-T2
      SGDT=-SGDT
  130 SI=S1
      DO 150 I=1,2
      TJ=TA
      DO 140 J=1,2
      ZIJ=TJ-SI
      R=SQRT(DSQ+ZIJ*ZIJ)
      W=R+ZIJ
      IF(ZIJ.LT.0.)W=DSQ/(R-ZIJ)
      V=R-ZIJ
      IF(ZIJ.GT.0.)V=DSQ/(R+ZIJ)
      IF(J.EQ.1)V1=V
      IF(J.EQ.1)W1=W
      EGZ(I,J)=CEXP(GAM*ZIJ)
  140 TJ=TB
      CALL EXPJ(GAM*V1,GAM*V,GP(I))
      CALL EXPJ(GAM*W1,GAM*W,GM(I))
  150 SI=S2
      CST=-ETA/(8.*PI*SGDS*SGDT)
      P11=CST*(GM(2)*EGZ(2,2)+GP(2)/EGZ(2,2)
     2-CGDS*(GM(1)*EGZ(1,2)+GP(1)/EGZ(1,2)))
      P12=CST*(-GM(2)*EGZ(2,1)-GP(2)/EGZ(2,1)
     2+CGDS*(GM(1)*EGZ(1,1)+GP(1)/EGZ(1,1)))
      P21=CST*(GM(1)*EGZ(1,2)+GP(1)/EGZ(1,2)
     2-CGDS*(GM(2)*EGZ(2,2)+GP(2)/EGZ(2,2)))
      P22=CST*(-GM(1)*EGZ(1,1)-GP(1)/EGZ(1,1)
     2+CGDS*(GM(2)*EGZ(2,1)+GP(2)/EGZ(2,1)))
      RETURN
      END
```

Fig. 13b. Subroutine GGMM

the test monopole with origin at the apparent intersection. S1 and S2 denote the s coordinates of the endpoints of the test monopole. Similarly, let t measure distance along the axis of the expansion monopole with origin at the apparent intersection. T1 and T2 denote the t coordinates of the endpoints of the expansion monopole. Let $\hat{s}$ and $\hat{t}$ be unit vectors parallel with the positive s and t axes, respectively. Then CPSI = $\hat{s} \cdot \hat{t} = \cos \psi$. The monopole lengths are d_s and d_t, and the remaining input data are defined as follows:

CGDS	$\cosh \gamma d_s$
SGD1	$\sinh \gamma d_s$
SGD2	$\sinh \gamma d_t$

GGMM calls EXPJ for the exponential integrals.

The output data from GGMM are the impedances P11, P12, P21, and P22. In defining these impedances, the reference direction is from S1 to S2 for the current on monopole s, and from T1 to T2 for the current on monopole t. In the impedance P_{ij}, the first subscript is 1 or 2 if the test dipole has terminals at S1 or S2 on monopole s. The second subscript is 1 or 2 if the expansion dipole has terminals at T1 or T2 on monopole t. The endpoint coordinates S1, S2, T1 and T2 may be positive or negative. The monopole lengths d_s and d_t are assumed positive in defining the input data CGDS, SGD1 and SGD2.

For parallel monopoles, CPSI = 1 or -1. S1, S2, T1 and T2 are cartesian coordinates for parallel monopoles and spherical coordinates for skew monopoles. For skew monopoles, the radial coordinates S1, S2, T1 and T2 tend to infinity as the angle ψ tends to zero or π. Therefore, if the monopoles are within 4.5° of being parallel, they are approximated by parallel dipoles.

APPENDIX 7. Subroutine EXPJ

Subroutine EXPJ, listed in Fig. 14, evaluates the exponential integral defined as follows:

$$(2) \qquad W12 = \int_{V1}^{V2} \frac{e^{-v}\,dv}{v} = E_1(V1) - E_1(V2) + j\,2n\pi$$

where the integration path is the straight line from V1 to V2 on the complex v plane and

$$(3) \qquad E_1(z) = \int_{z}^{\infty} \frac{e^{-t}\,dt}{t}$$

```
      SUBROUTINE EXPJ(V1,V2,W12)
      COMPLEX EC,E15,S,T,UC,VC,V1,V2,W12,Z
      DIMENSION V(21),W(21),D(16),E(16)
      DATA V/   0.22284667E 00,
     20.11889321E 01,0.29927363E 01,0.57751436E 01,0.98374674E 01,
     20.15982874E 02,0.93307812E-01,0.49269174E 00,0.12155954E 01,
     20.22699495E 01,0.36676227E 01,0.54253366E 01,0.75659162E 01,
     20.10120228E 02,0.13130282E 02,0.16654408E 02,0.20776479E 02,
     20.25623894E 02,0.31407519E 02,0.38530683E 02,0.48026086E 02/
      DATA W/   0.45896460E 00,
     20.41700083E 00,0.11337338E 00,0.10399197E-01,0.26101720E-03,
     20.89854791E-06,0.21823487E 00,0.34221017E 00,0.26302758E 00,
     20.12642582E 00,0.40206865E-01,0.85638778E-02,0.12124361E-02,
     20.11167440E-03,0.64599267E-05,0.22263169E-06,0.42274304E-08,
     20.39218973E-10,0.14565152E-12,0.14830270E-15,0.16005949E-19/
      DATA D/   0.22495842E 02,
     2 0.74411568E 02,-0.41431576E 03,-0.78754339E 02, 0.11254744E 02,
     2 0.16021761E 03,-0.23862195E 03,-0.50094687E 03,-0.68487854E 02,
     2 0.12254778E 02,-0.10161976E 02,-0.47219591E 01, 0.79729681E 01,
     2-0.21069574E 02, 0.22046490E 01, 0.89728244E 01/
      DATA E/   0.21103107E 02,
     2-0.37959787E 03,-0.97489220E 02, 0.12900672E 03, 0.17949226E 02,
     2-0.12910931E 03,-0.55705574E 03, 0.13524801E 02, 0.14696721E 03,
     2 0.17949528E 02,-0.32981014E 00, 0.31028836E 02, 0.81657657E 01,
     2 0.22236961E 02, 0.39124892E 02, 0.81636799E 01/
      Z=V1
      DO 100 JIM=1,2
      X=REAL(Z)
      Y=AIMAG(Z)
      E15=(.0,.0)
      AB=CABS(Z)
      IF(AB.EQ.0.)GO TO 90
      IF(X.GE.0. .AND. AB.GT.10.)GO TO 80
      YA=ABS(Y)
      IF(X.LE.0. .AND. YA.GT.10.)GO TO 80
      IF(YA-X.GE.17.5.OR.YA.GE.6.5.OR.X+YA.GE.5.5.OR.X.GE.3.)GO TO 20
      IF(X.LE.-9.)GO TO 40
      IF(YA-X.GE.2.5)GO TO 50
      IF(X+YA.GE.1.5)GO TO 30
   10 N=6.+3.*AB
      E15=1./(N-1.)-Z/N**2
   15 N=N-1
      E15=1./(N-1.)-Z*E15/N
      IF(N.GE.3)GO TO 15
      E15=Z*E15-CMPLX(.577216+ALOG(AB),ATAN2(Y,X))
      GO TO 90
   20 J1=1
      J2=6
      GO TO 31
   30 J1=7
      J2=21
   31 S=(.0,.0)
      YS=Y*Y
      DO 32 I=J1,J2
      XI=V(I)+X
      CF=W(I)/(XI*XI+YS)
   32 S=S+CMPLX(XI*CF,-YA*CF)
      GO TO 54
   40 T3=X*X-Y*Y
      T4=2.*X*YA
      T5=X*T3-YA*T4
      T6=X*T4+YA*T3
```

Fig. 14a. Subroutine EXPJ

```
      UC=CMPLX(D(11)+D(12)*X+D(13)*T3+T5-E(12)*YA-E(13)*T4,
     2        E(11)+E(12)*X+E(13)*T3+T6+D(12)*YA+D(13)*T4)
      VC=CMPLX(D(14)+D(15)*X+D(16)*T3+T5-E(15)*YA-E(16)*T4,
     2        E(14)+E(15)*X+E(16)*T3+T6+D(15)*YA+D(16)*T4)
      GO TO 52
50    T3=X*X-Y*Y
      T4=2.*X*YA
      T5=X*T3-YA*T4
      T6=X*T4+YA*T3
      T7=X*T5-YA*T6
      T8=X*T6+YA*T5
      T9=X*T7-YA*T8
      T10=X*T8+YA*T7
      UC=CMPLX(D(1)+D(2)*X+D(3)*T3+D(4)*T5+D(5)*T7+T9-(E(2)*YA+E(3)*T4
     2+E(4)*T6+E(5)*T8),E(1)+E(2)*X+E(3)*T3+E(4)*T5+E(5)*T7+T10+
     3(D(2)*YA+D(3)*T4+D(4)*T6+D(5)*T8))
      VC=CMPLX(D(6)+D(7)*X+D(8)*T3+D(9)*T5+D(10)*T7+T9-(E(7)*YA+E(8)*T4
     2+E(9)*T6+E(10)*T8),E(6)+E(7)*X+E(8)*T3+E(9)*T5+E(10)*T7+T10+
     3(D(7)*YA+D(8)*T4+D(9)*T6+D(10)*T8))
52    EC=UC/VC
      S=EC/CMPLX(X,YA)
54    EX=EXP(-X)
      T=EX*CMPLX(COS(YA),-SIN(YA))
      E15=S*T
56    IF(Y.LT.0.)E15=CONJG(E15)
      GO TO 90
80    E15=.409319/(Z+.193044)+.421831/(Z+1.02666)+.147126/(Z+2.56788)+
     2.206335E-1/(Z+4.90035)+.107401E-2/(Z+8.18215)+.158654E-4/(Z+
     312.7342)+.317031E-7/(Z+19.3957)
      E15=E15*CEXP(-Z)
90    IF(JIM.EQ.1)W12=E15
100   Z=V2
      Z=V2/V1
      TH=ATAN2(AIMAG(Z),REAL(Z))-ATAN2(AIMAG(V2),REAL(V2))
     2+ATAN2(AIMAG(V1),REAL(V1))
      AB=ABS(TH)
      IF(AB.LT.1.)TH=.0
      IF(TH.GT.1.)TH=6.2831853
      IF(TH.LT.-1.)TH=-6.2831853
      W12=W12-E15+CMPLX(.0,TH)
      RETURN
      END
```

Fig. 14b. Subroutine EXPJ

The exponential integral $E_1(z)$ is defined in Reference 3. To generate W12, subroutine EXPJ calculates $E_1(V1)$, subtracts $E_1(V2)$ and adds $j2n\pi$. The term $j2n\pi$ is determined by the requirement that W12 vanish in the limit as V1 approaches V2. The integer n may assume values of -1, 0 or +1. If the integration path does not cross the negative real axis in the v plane, n is zero. The term $j2n\pi$ is calculated below statement 100.

APPENDIX 8. Subroutine GANT1

Subroutine GANT1, listed in Fig. 15, considers the wire structure as an antenna. In the input data, VG(J) is the voltage of a generator at point IA(J) of segment J. VG(JJ) is the voltage of a generator at point IB(J) of segment J. The DO LOOP ending with statement 50 uses the delta-gap model to determine the excitation voltages CJ(I) for all the dipole modes. These are also stored temporarily in CG(I). Then subroutine SQROT is called to obtain a solution of the simultaneous linear equations. SQROT stores the solution (the loop currents) in CJ(I).

In the DO LOOP ending at statement 80, the complex power input is calculated and stored in Y11. GG denotes the time-average power input and is the real part of Y11. If the antenna has only one voltage generator (with unit voltage and zero phase angle), then Y11 also denotes the antenna admittance and Z11 is the antenna impedance at that port.

Subroutine RITE is called to make the transformation from the loop currents CJ(I) to the branch currents CG(J). If IWR is a positive integer, RITE will write out the list of branch currents.

Finally, GANT1 calculates the radiation efficiency EFF. PIN denotes the time-average power input. Subroutine GDISS is called to obtain the time-average power dissipated. DISS is the total power dissipated in the lumped loads and the imperfectly-conducting wire. PRAD is the time-average power radiated, defined by the difference between PIN and DISS. If the antenna has perfect conductivity and purely reactive loads, the radiation efficiency is considered to be 100 per cent.

APPENDIX 9. Subroutine SQROT

Subroutine SQROT is listed in Fig. 16. This subroutine considers the matrix equation ZI = V which represents a system of simultaneous linear equations. If the square matrix Z is symmetric, SQROT is useful for obtaining the solution I with V given. NEQ denotes the number of simultaneous equations and the size of the matrix Z.

On entry to SQROT, S is the excitation column V. On exit, the solution I is stored in S. Let Z(I,J) denote the symmetric square

```
      SUBROUTINE GANT1(IA,IB,INM,IWR,I1,I2,I3,I12,JA,JB,MD,N,ND,NM,AM
     2,C,CJ,CG,CMM,D,EFF,GAM,GG,CGD,SGD,VG,Y11,Z11,ZLD,ZS)
      COMPLEX C(1),CJ(1),CGD(1),SGD(1),VG(1),ZLD(1),Y11,Z11,ZS,GAM,CG(1)
      DIMENSION D(1),IA(1),IB(1),JA(1),JB(1)
      DIMENSION I1(1),I2(1),I3(1),MD(INM,4),ND(1)
2     FORMAT(1X,1I5,8F10.2)
5     FORMAT(1H0)
      DO 50 I=1,N
      CJ(I)=(.0,.0)
      K=JA(I)
      DO 40 KK=1,2
      KA=IA(K)
      KB=IB(K)
      JJ=K
      FI=1.
      IF(KB.EQ.I2(I))GO TO 36
      IF(KB.EQ.I1(I))FI=-1.
      CJ(I)=CJ(I)+FI*VG(JJ)
      GO TO 40
36    IF(KA.EQ.I3(I))FI=-1.
      JJ=K+NM
      CJ(I)=CJ(I)+FI*VG(JJ)
40    K=JB(I)
50    CONTINUE
      DO 55 I=1,N
55    CG(I)=CJ(I)
      CALL SQROT(C,CJ,0,I12,N)
      I12=2
      Y11=(.0,.0)
      DO 80 I=1,N
80    Y11=Y11+CJ(I)*CONJG(CG(I))
      CALL RITE(IA,IB,INM,IWR,I1,I2,I3,MD,ND,NM,CJ,CG)
      GG=REAL(Y11)
      Z11=1./Y11
      PIN=GG
      CALL      GDISS(AM,CG,CMM,D,DISS,GAM,NM,SGD,ZLD,ZS)
      PRAD=PIN-DISS
      EFF=100.*PRAD/PIN
      RETURN
      END
```

Fig. 15. Subroutine GANT1

```
      SUBROUTINE SQROT(C,S,IWR,I12,NEQ)
      COMPLEX C(1),S(1),SS
2     FORMAT(1X,1I5,1F10.3,1F15.7,1F10.0,2F15.6)
3     FORMAT(1H0)
      N=NEQ
      IF(I12.EQ.2)GO TO 20
      C(1)=CSQRT(C(1))
      DO 4 K=2,N
4     C(K)=C(K)/C(1)
      DO 10 I=2,N
      IMO=I-1
      IPO=I+1
      ID=(I-1)*N-(I*I-I)/2
      II=ID+I
      DO 5 L=1,IMO
      LI=(L-1)*N-(L*L-L)/2+I
5     C(II)=C(II)-C(LI)*C(LI)
      C(II)=CSQRT(C(II))
      IF(IPO.GT.N)GO TO 10
      DO 8 J=IPO,N
      IJ=ID+J
      DO 6 M=1,IMO
      MD=(M-1)*N-(M*M-M)/2
      MI=MD+I
      MJ=MD+J
    6 C(IJ)=C(IJ)-C(MJ)*C(MI)
8     C(IJ)=C(IJ)/C(II)
10    CONTINUE
20    S(1)=S(1)/C(1)
      DO 30 I=2,N
      IMO=I-1
      DO 25 L=1,IMO
      LI=(L-1)*N-(L*L-L)/2+I
25    S(I)=S(I)-C(LI)*S(L)
      II=(I-1)*N-(I*I-I)/2+I
30    S(I)=S(I)/C(II)
      NN=((N+1)*N)/2
      S(N)=S(N)/C(NN)
      NMO=N-1
      DO 40 I=1,NMO
      K=N-I
      KPO=K+1
      KD=(K-1)*N-(K*K-K)/2
      DO 35 L=KPO,N
      KL=KD+L
35    S(K)=S(K)-C(KL)*S(L)
      KK=KD+K
40    S(K)=S(K)/C(KK)
      IF(IWR.LE.0) GO TO 100
      CNOR=.0
      DO 50 I=1,N
      SA=CABS(S(I))
50    IF(SA.GT.CNOR)CNOR=SA
      IF(CNOR.LE.0.)CNOR=1.
      DO 60 I=1,N
      SS=S(I)
      SA=CABS(SS)
      SNOR=SA/CNOR
      PH=.0
      IF(SA.GT.0.)PH=57.29578*ATAN2(AIMAG(SS),REAL(SS))
60    WRITE(6,2)I,SNOR,SA,PH,SS
      WRITE(6,3)
100   RETURN
      END
```

Fig. 16. Subroutine SQROT

matrix. On entry to SQROT, the upper-right triangular portion of Z(I,J) is stored by rows in C(K) with

(4) K = (I - 1)*NEQ - (I*I - I) / 2 + J

If I12 = 1, SQROT will transform the symmetric matrix into the auxiliary matrix (implicit inverse), store the result in C(K) and use the auxiliary matrix to solve the simultaneous equations. If I12 = 2, this indicates that C(K) already contains the auxiliary matrix.

The transformation from the symmetric matrix to the auxiliary matrix is programmed above statement 10, and the solution of the simultaneous equations is programmed in statements 20 to 40. If IWR is positive, the program below statement 40 will write the solution.

SQROT uses the square root method described in Reference 4. The original symmetric matrix Z and the upper triangular auxiliary matrix A are related by

(5) Z = A' A

where A' is the transpose of A.

In the thin-wire application, SQROT must be called with I12 = 1 before it is called with I12 = 2. With a large matrix, the execution time in SQROT is much smaller with I12 = 2 than with I12 = 1.

APPENDIX 10. Subroutine RITE

Subroutine RITE is listed in Fig. 17. Given the list of loop currents CJ(I), this subroutine generates a list of branch currents CG(J). CG(J) and CG(JJ) denote the currents at IA(J) and IB(J), respectively, on the wire segment J, where JJ = J + NM. If IWR is a positive integer, the program below statement 110 writes a list of the branch currents. The symbols in this list are defined as follows:

K	the segment number
ACJ	normalized current magnitude at IA(K)
BCJ	normalized current magnitude at IB(K)
PA	phase of current at IA(K)
PB	phase of current at IB(K)
CJA	complex current at IA(K)
CJB	complex current at IB(K)

The phase angles PA and PB are in degrees. Even if IWR is negative, RITE generates the branch-current list for use in subroutine GDISS.

```
      SUBROUTINE RITE(IA,IB,INM,IWR,I1,I2,I3,MD,ND,NM,CJ,CG)
      COMPLEX CJ(1),CG(1),CJA,CJB
      DIMENSION IA(1),IB(1),I1(1),I2(1),I3(1),MD(INM,4),ND(1)
2     FORMAT(1X,1I5,2F10.3,2F10.0,4F15.6)
5     FORMAT(1H0)
      AMAX=.0
      DO 100 K=1,NM
      KA=IA(K)
      KB=IB(K)
      CJA=(.0,.0)
      CJB=(.0,.0)
      NDK=ND(K)
      DO 40 II=1,NDK
      I=MD(K,II)
      FI=1.
      IF(KB.EQ.I2(I))GO TO 36
      IF(KB.EQ.I1(I))FI=-1.
      CJA=CJA+FI*CJ(I)
      GO TO 40
36    IF(KA.EQ.I3(I))FI=-1.
      CJB=CJB+FI*CJ(I)
40    CONTINUE
      CG(K)=CJA
      KK=K+NM
      CG(KK)=CJB
      ACJ=CABS(CJA)
      BCJ=CABS(CJB)
      IF(ACJ.GT.AMAX)AMAX=ACJ
      IF(BCJ.GT.AMAX)AMAX=BCJ
100   CONTINUE
      IF(IWR.GT.0)GO TO 110
      RETURN
110   IF(AMAX.LE.0.)AMAX=1.
      DO 200 K=1,NM
      CJA=CG(K)
      KK=K+NM
      CJB=CG(KK)
      ACJ=CABS(CJA)/AMAX
      BCJ=CABS(CJB)/AMAX
      PA=57.29578*ATAN2(AIMAG(CJA),REAL(CJA))
      PB=57.29578*ATAN2(AIMAG(CJB),REAL(CJB))
200   WRITE(6,2)K,ACJ,BCJ,PA,PB,CJA,CJB
      WRITE(6,5)
      RETURN
      END
```

Fig. 17. Subroutine RITE

APPENDIX 11. Subroutine GDISS

Subroutine GDISS is listed in Fig. 18. This subroutine uses Eq. 50 of Reference 1 to calculate the time-average power dissipated in the imperfectly conducting wire. This is accomplished in the DO LOOP terminating at statement 100. The power dissipated in the lumped loads is calculated in the DO LOOP terminating with statement 140. DISS denotes the time-average power dissipated in the wire and the loads.

APPENDIX 12. Subroutine GNFLD

Subroutine GNFLD, listed in Fig. 19, inputs the loop currents CJ(I), calls GNF for the near-zone field of each wire segment, and sums over all the segments to obtain the near-zone field of the wire antenna or the near-zone scattered field of the wire scatterer. EX, EY and EZ denote the cartesian components of this field at the observation point (XP,YP,ZP). This calculated field does not include the incident fields of the magnetic frills or loops associated with generators on the antenna. It also does not include the radiation from the polarization currents in the dielectric insulation.

This subroutine could be simplified and speeded by inputting the branch currents CG(J) instead of the loop currents CJ(I). However, this would increase the storage requirements because the far-field subroutine GFFLD would have to store the branch currents induced by the phi-polarized and theta-polarized incident waves.

APPENDIX 13. Subroutine GNF

Subroutine GNF, listed in Fig. 20, uses Eqs. 75 and 76 of Reference 1 to calculate the near-zone electric field of a sinusoidal electric monopole with endpoints at (XA,YA,ZA) and (XB,YB,ZB). The observation point is at (X,Y,Z). EX1, EY1 and EZ1 are the components of the field generated by the mode with unit current at (XA,YA,ZA). EX2, EY2 and EZ2 denote the field generated by the mode with unit current at (XB,YB,ZB). GNF is similar to GGS, and Appendix 5 defines many of the symbols used in both subroutines.

APPENDIX 14. Subroutine GFFLD

The far-field subroutine GFFLD, listed in Fig. 21, is discussed in section II. In antenna gain calculations with INC = 0, the loop currents CJ(I) are employed by GFFLD to calculate the far-zone field. The field of each segment is obtained by calling GFF, and a summation over all the segments yields the field of the antenna.

In a bistatic scattering situation with INC = 2, the input data include the loop currents EP and ET induced by phi-polarized and theta-polarized incident waves. These currents were calculated by GFFLD in a

```
      SUBROUTINE GDISS(AM,CG,CMM,D,DISS,GAM,NM,SGD,ZLD,ZS)
      COMPLEX CG(1),SGD(1),ZLD(1),CJA,CJB,GAM,ZS
      DIMENSION D(1)
      DATA PI/3.14159/
      DISS=.0
      IF(CMM.LE.0.)GO TO 120
      ALPH=REAL(GAM)
      BETA=AIMAG(GAM)
      RH=REAL(ZS)/(4.*PI*AM)
      DO 100 K=1,NM
      DK=D(K)
      DEN=CABS(SGD(K))**2
      EAD=EXP(ALPH*DK)
      CAD=(EAD+1./EAD)/2.
      CBD=COS(BETA*DK)
      SAD=DK
      IF(ALPH.NE.0.)SAD=(EAD-1./EAD)/(2.*ALPH)
      SBD=DK
      IF(BETA.NE.0.)SBD=SIN(BETA*DK)/BETA
      FA=RH*(SAD*CAD-SBD*CBD)/DEN
      FB=2.*RH*(CAD*SBD-SAD*CBD)/DEN
      CJA=CG(K)
      L=K+NM
      CJB=CG(L)
  100 DISS=DISS+FA*(CABS(CJA)**2+CABS(CJB)**2)
     2+FB*(REAL(CJA)*REAL(CJB)+AIMAG(CJA)*AIMAG(CJB))
  120 DO 140 J=1,NM
      K=J+NM
  140 DISS=DISS+REAL(ZLD(J))*(CABS(CG(J))**2)
     2+REAL(ZLD(K))*(CABS(CG(K))**2)
      RETURN
      END
```

Fig. 18. Subroutine GDISS

```
      SUBROUTINE GNFLD(IA,IB,INM,I1,I2,I3,MD,N,ND,NM,AM,CGD,SGD,ETA,GAM
     2,CJ,D,X,Y,Z,XP,YP,ZP,EX,EY,EZ)
      COMPLEX EX,EY,EZ,EX1,EY1,EZ1,EX2,EY2,EZ2,ETA,GAM
      COMPLEX CJ(1),CGD(1),SGD(1)
      DIMENSION IA(1),IB(1),I1(1),I2(1),I3(1),D(1),X(1),Y(1),Z(1)
      DIMENSION MD(INM,4),ND(1)
      DATA PI,TP/3.14159,6.28318/
      EX=(.0,.0)
      EY=(.0,.0)
      EZ=(.0,.0)
      DO 140 K=1,NM
      KA=IA(K)
      KB=IB(K)
      CALL GNF(X(KA),Y(KA),Z(KA),X(KB),Y(KB),Z(KB),XP,YP,ZP,AM,D(K)
     2,CGD(K),SGD(K),ETA,GAM,EX1,EY1,EZ1,EX2,EY2,EZ2)
      NDK=ND(K)
      DO 140 II=1,NDK
      I=MD(K,II)
      FI=1.
      IF(KB.EQ.I2(I))GO TO 136
      IF(KB.EQ.I1(I))FI=-1.
      EX=EX+FI*EX1*CJ(I)
      EY=EY+FI*EY1*CJ(I)
      EZ=EZ+FI*EZ1*CJ(I)
      GO TO 140
  136 IF(KA.EQ.I3(I))FI=-1.
      EX=EX+FI*EX2*CJ(I)
      EY=EY+FI*EY2*CJ(I)
      EZ=EZ+FI*EZ2*CJ(I)
  140 CONTINUE
      RETURN
      END
```

Fig. 19. Subroutine GNFLD

```
      SUBROUTINE GNF(XA,YA,ZA,XB,YB,ZB,X,Y,Z,AM,DS,CGDS,SGDS,ETA,GAM
     2,EX1,EY1,EZ1,EX2,EY2,EZ2)
      COMPLEX EJA,EJB,EJ1,EJ2,ER1,ER2,ES1,ES2,SGDS,GAM,CST,CGDS,ETA
      COMPLEX EX1,EY1,EZ1,EX2,EY2,EZ2
      DATA PI/3.14159/
      CAS=(XB-XA)/DS
      CBS=(YB-YA)/DS
      CGS=(ZB-ZA)/DS
      SZ=(X-XA)*CAS+(Y-YA)*CBS+(Z-ZA)*CGS
      ZZ1=SZ
      ZZ2=SZ-DS
      XXZ=X-XA-SZ*CAS
      YYZ=Y-YA-SZ*CBS
      ZZZ=Z-ZA-SZ*CGS
      RS=XXZ**2+YYZ**2+ZZZ**2
      R1=SQRT(RS+ZZ1**2)
      EJA=CEXP(-GAM*R1)
      EJ1=EJA/R1
      R2=SQRT(RS+ZZ2**2)
      EJB=CEXP(-GAM*R2)
      EJ2=EJB/R2
      ES1=EJ2-EJ1*CGDS
      ES2=EJ1-EJ2*CGDS
      ER1=(.0,.0)
      ER2=(.0,.0)
      AMS=AM*AM
      IF(RS.LT.AMS)GO TO 80
      CTH1=ZZ1/R1
      CTH2=ZZ2/R2
      ER1=( EJA*SGDS+EJA*CGDS*CTH1-EJB*CTH2)/RS
      ER2=(-EJB*SGDS+EJB*CGDS*CTH2-EJA*CTH1)/RS
   80 CST=ETA/(4.*PI*SGDS)
      EX1=CST*(ES1*CAS+ER1*XXZ)
      EY1=CST*(ES1*CBS+ER1*YYZ)
      EZ1=CST*(ES1*CGS+ER1*ZZZ)
      EX2=CST*(ES2*CAS+ER2*XXZ)
      EY2=CST*(ES2*CBS+ER2*YYZ)
      EZ2=CST*(ES2*CGS+ER2*ZZZ)
      RETURN
      END
```

Fig. 20. Subroutine GNF

```
      SUBROUTINE GFFLD(IA,IB,INC,INM,IWR,I1,I2,I3,I12,MD,N,ND,NM,AM
     2,ACSP,ACST,C,CGD,CG,CJ,CMM,D,ECSP,ECST,EP,ET,EPP,ETT,EPPS,EPTS
     3,ETPS,ETTS,GG,GPP,GTT,PH,SGD,SCSP,SCST,SPPM,SPTM,STPM,STTM,TH
     4,X,Y,Z,ZLD,ZS,ETA,GAM)
      COMPLEX CJI,ET1,ET2,EP1,EP2,EPPS,ETTS,EPTS,ETPS,ZS,VP,VT
      COMPLEX C(1),CJ(1),EP(1),ET(1),EPP(1),ETT(1),ZLD(1)
      COMPLEX ETA,GAM,CGD(1),SGD(1),CG(1)
      DIMENSION IA(1),IB(1),I1(1),I2(1),I3(1),ND(1),MD(INM,4)
      DIMENSION D(1),X(1),Y(1),Z(1)
      DATA PI,TP/3.14159,6.28318/
      CJI=-4.*PI/(ETA*GAM)
      GGG=REAL(1./ETA)
      THR=.0174533*TH
      CTH=COS(THR)
      STH=SIN(THR)
      PHR=.0174533*PH
      CPH=COS(PHR)
      SPH=SIN(PHR)
      DO 130 I=1,N
      ETT(I)=(.0,.0)
  130 EPP(I)=(.0,.0)
      DO 140 K=1,NM
      KA=IA(K)
      KB=IB(K)
      CALL GFF(X(KA),Y(KA),Z(KA),X(KB),Y(KB),Z(KB),D(K)
     2,CGD(K),SGD(K),CTH,STH,CPH,SPH,GAM,ETA,ET1,ET2,EP1,EP2)
      NDK=ND(K)
      DO 140 II=1,NDK
      I=MD(K,II)
      FI=1.
      IF(KB.EQ.I2(I))GO TO 136
      IF(KB.EQ.I1(I))FI=-1.
      EPP(I)=EPP(I)+FI*EP1
      ETT(I)=ETT(I)+FI*ET1
      GO TO 140
  136 IF(KA.EQ.I3(I))FI=-1.
      EPP(I)=EPP(I)+FI*EP2
      ETT(I)=ETT(I)+FI*ET2
  140 CONTINUE
      EPPS=(.0,.0)
      ETTS=(.0,.0)
      IF(INC.EQ.0)GO TO 200
      IF(INC.EQ.2)GO TO 170
      DO 150 I=1,N
      ET(I)=ETT(I)*CJI
  150 EP(I)=EPP(I)*CJI
      CALL SQROT(C,EP,0,I12,N)
      I12=2
      CALL SQROT(C,ET,0,I12,N)
      CALL RITE(IA,IB,INM,IWR,I1,I2,I3,MD,ND,NM,EP,CG)
      CALL GDISS(AM,CG,CMM,D,PDIS,GAM,NM,SGD,ZLD,ZS)
      CALL RITE(IA,IB,INM,IWR,I1,I2,I3,MD,ND,NM,ET,CG)
      CALL GDISS(AM,CG,CMM,D,TDIS,GAM,NM,SGD,ZLD,ZS)
      ACSP=PDIS/GGG
      ACST=TDIS/GGG
      PIN=.0
      TIN=.0
      DO 164 I=1,N
      VP=CJI*EPP(I)
      VT=CJI*ETT(I)
      PIN=PIN+REAL(VP*CONJG(EP(I)))
  164 TIN=TIN+REAL(VT*CONJG(ET(I)))
```

Fig. 21a. Subroutine GFFLD

```
      ECSP=PIN/GGG
      ECST=TIN/GGG
      SCSP=ECSP-ACSP
      SCST=ECST-ACST
170   EPTS=(.0,.0)
      ETPS=(.0,.0)
      DO 180 I=1,N
      EPPS=EPPS+EP(I)*EPP(I)
      EPTS=EPTS+EP(I)*ETT(I)
      ETTS=ETTS+ET(I)*ETT(I)
180   ETPS=ETPS+ET(I)*EPP(I)
      SPPM=2.*TP*(CABS(EPPS)**2)
      SPTM=2.*TP*(CABS(EPTS)**2)
      STPM=2.*TP*(CABS(ETPS)**2)
      STTM=2.*TP*(CABS(ETTS)**2)
      RETURN
200   DO 260 I=1,N
      ETTS=ETTS+CJ(I)*ETT(I)
260   EPPS=EPPS+CJ(I)*EPP(I)
      APP=CABS(EPPS)
      ATT=CABS(ETTS)
      GPP=4.*PI*APP*APP*GGG/GG
      GTT=4.*PI*ATT*ATT*GGG/GG
      RETURN
      END
```

Fig. 21b. Subroutine GFFLD

previous call for the backscattering situation with INC = 1. Thus, a bistatic call must be preceded by a backscatter call.

EPP(I) and ETT(I) denote the phi-polarized and theta-polarized far-zone fields of dipole mode I with unit terminal current. In a backscattering situation, the excitation voltages EP(I) and ET(I) are obtained by multiplying EPP and ETT by the constant CJI. (See Eqs. 38, 39 and 40 in Reference 1.) Then calls are made to SQROT which stores the solution (the induced loop currents) in EP(I) and ET(I). RITE is called for the branch currents CG(J), and GDISS is called for the time-average power dissipated in the imperfectly conducting wire and the lumped loads. This power is denoted PDIS and TDIS for phi-polarized and theta-polarized incident waves, respectively.

In scattering problems, the incident plane wave has unit electric field intensity at the coordinate origin. GGG denotes the time-average power density of the incident wave at the origin. ACSP and ACST denote the absorption cross sections for the phi and theta polarizations.

PIN and TIN denote the time-average power input to the wire structure, delivered by the equivalent voltage generators VP and VT at the terminals. PIN and TIN apply for the phi and theta polarizations, respectively. The time-average power input is regarded as the sum of the time-average power dissipated (in the wire and the lumped loads) and the time-average power radiated or scattered by the wire. ECSP and ECST denote the extinction cross sections and SCSP and SCST are the scattering cross sections.

The distant field is calculated in the DO LOOP ending with statement 180 for scattering situations, and in the DO LOOP ending with statement 260 for the antenna situation. In these fields, the range dependence is suppressed as in Eq. (1).

The radar cross sections (echo areas) SPPM, SPTM, STPM and STTM are defined as in Eq. 72 of Reference 1 with the incident power density (S_i or GGG) evaluated at the coordinate origin. The user selects the location of the origin when supplying the input data for the coordinates of all the points on the wire.

For an antenna, the following definition is employed for the power gain:

$$(6) \qquad G_p(\theta,\phi) = \lim_{r \to \infty} \; 4\pi r^2 e^{2\alpha r} S(r,\theta,\phi) \; / \; P_i$$

where P_i (or GG in the program) denotes the time-average power input and $S(r,\theta,\phi)$ is the time-average power density in the radiated field. For an antenna in a lossless medium, α vanishes and Eq. (6) reduces to the standard definition of power gain. Without the factor $e^{2\alpha r}$ in Eq. (6), the power gain would vanish for a finite antenna in a conducting medium. GPP and GTT denote the power gains associated with the phi-polarized and theta-polarized components of the field, respectively.

APPENDIX 15. Subroutine GFF

Subroutine GFF, listed in Fig. 22, uses the equations in Appendix 2 of Reference 1 to calculate the far-zone field of a sinusoidal electric monopole. The monopole has endpoints (XA,YA,ZA) and (XB,YB,ZB). EP1 and ET1 denote E_ϕ and E_θ for the mode with unit current at (XA,YA,ZA). EP2 and ET2 denote the fields for the mode with unit current at (XB,YB,ZB). The range dependence is suppressed as in Eq. (1). The far field vanishes in the endfire direction where GK = 0.

```
      SUBROUTINE  GFF(XA,YA,ZA,XB,YB,ZB,D,
     2CGD,SGD,CTH,STH,CPH,SPH,
     2GAM,ETA,ET1,ET2,EP1,EP2)
      COMPLEX ET1,ET2,EP1,EP2,GAM,ETA
      COMPLEX GD,CGD,SGD,EGD
      COMPLEX EGFA,EGFB,EGGD,ESA,ESB
      COMPLEX CST
      FP=12.56637
      XAB=XB-XA
      YAB=YB-YA
      ZAB=ZB-ZA
      CA=XAB/D
      CB=YAB/D
      CG=ZAB/D
      G=(CA*CPH+CB*SPH)*STH+CG*CTH
      GK=1.-G*G
      ET1=(.0,.0)
      ET2=(.0,.0)
      EP1=(.0,.0)
      EP2=(.0,.0)
      IF(GK.LT..001)GO TO 200
      FA=(XA*CPH+YA*SPH)*STH+ZA*CTH
      FB=(XB*CPH+YB*SPH)*STH+ZB*CTH
      EGFA=CEXP(GAM*FA)
      EGFB=CEXP(GAM*FB)
      EGGD=CEXP(GAM*G*D)
      CST=ETA/(GK*SGD*FP)
      ESA=CST*EGFA*(EGGD-G*SGD-CGD)
      ESB=CST*EGFB*(1./EGGD+G*SGD-CGD)
      T=(CA*CPH+CB*SPH)*CTH-CG*STH
      P=-CA*SPH+CB*CPH
      ET1=T*ESA
      ET2=T*ESB
      EP1=P*ESA
      EP2=P*ESB
  200 CONTINUE
      RETURN
      END
```

Fig. 22. Subroutine GFF

U.S. GOVERNMENT PRINTING OFFICE: 1974-737-724/91 REGION NO. 3-11