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A PROGRAM FOR COMPUTING NEAR FIELDS OF THIN WIRE ANTENNAS

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ABSTRACT

A user-oriented computer program is presented and described for analyzing the near fields of thin wire antennas. The program is based on the method of moments and is an extension of a program presented earlier for computing far-field and current distributions. In general the wires of a given configuration can be arbitrarily bent and can be excited or loaded at arbitrary points along their lengths. It is also possible to include wire junctions enabling treatment of special configurations such as wire crosses and supporting wires for long antennas. The subsectional approach used provides accurate results as close as one subsection length from the nearest wire surface.

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I. INTRODUCTION

In this report a method is presented for calculating the near fields of thin wire antennas. The method is based on the reciprocity theorem for electromagnetic fields and can be applied to problems involving thin and arbitrarily bent wires where each wire length L and radius a are such that $L/a \gg 1$ and $a \ll \lambda$, the wavelength. A user-oriented computer program based on this method is presented in the Appendix and instructions for using the program are included in Section IV.

It is assumed here that the current distribution for a given problem is known and furthermore, that it has been computed using a program provided earlier through this project [1]. The portions of that program which are necessary for computing the current corresponding to a given problem geometry are incorporated in the program of the Appendix. These are combined with a subroutine based on the work of Section II that is suitable for computing any given component of the near-zone electric field at any point near the wire structure. (This is subject to a restriction pointed out in the next paragraph.)

The current distribution is computed using the matrix methods suggested by Harrington [2,3]. In order to apply these methods each wire in the problem geometry is thought of as a number of short subsections or segments connected together. The program presented in the Appendix for near-field computations can be expected to provide accurate results up to (but not closer than) a distance equalling the largest of these segment lengths from any wire surface. Work is continuing on modifications that may provide accurate results in closer than this. However, this effort has been hampered by a lack of reliable experimental data corresponding to the regions and structures of interest.

There is another procedure, based on Harrington's work, that is also suitable for near-field computations [4]. A corresponding computer program is available, but not in user-oriented form. However, the method has been used in several instances to verify results obtained with the program of this report.

II. APPROACH BASED ON RECIPROCITY

For antenna problems the reciprocity theorem states that

$$\int_V \vec{E}_1 \cdot \vec{J}_2 dv = \int_V \vec{E}_2 \cdot \vec{J}_1 dv \tag{1}$$

where $\vec{J}_1$ and $\vec{J}_2$ are source current densities, and $\vec{E}_1$ and $\vec{E}_2$ are the corresponding electric fields. The reciprocity theorem can be used to find the near field at a given point near a radiating wire structure by considering $\vec{J}_1$ as the known current on the structure and $\vec{J}_2$ as the current of an infinitesimal testing dipole placed at the field point in question and oriented with the desired field component. Attention is restricted here to problems involving thin wires where the current of each wire flows only in its axial direction. If ℓ_1 denotes the wire structure and ℓ_2 the testing dipole then (1) can be written as

$$\int_{\ell_2} \vec{E}_1 \cdot I_2 d\vec{\ell}_2 = \int_{\ell_1} \vec{E}_2 \cdot I_1 d\vec{\ell}_1 \tag{2}$$

where I_1 and I_2 are axial currents with directions indicated by $d\vec{\ell}_1$ and $d\vec{\ell}_2$ respectively. For the infinitesimal dipole it is convenient to think of I_2 as constant over ℓ_2 as $\ell_2 \to 0$. Thus, (2) becomes

$$(E_1)_{\text{along } \ell_2} = \frac{1}{I_2 \ell_2} \int_{\ell_1} \vec{E}_2 \cdot I_1 d\vec{\ell}_1 \tag{3}$$

The current I_1 is known (calculated using the program provided in the Appendix and described earlier [1]) and $\vec{E}_2$, the field of the infinitesimal dipole, can be calculated easily. Hence, (3) is a useful starting point from which the desired field components can be found.

$\vec{E}_2$ can be calculated using the vector and scalar potentials as

$$\vec{E}_2 = - j\omega\mu\vec{A}_2 - \vec{\nabla}\phi_2 \tag{4}$$

where [5]

$$\vec{A}_2 = \frac{I_2\vec{\ell}_2}{4\pi R} e^{-jkR} \tag{5}$$

$$\phi_2 = - \frac{1}{j\omega\varepsilon} \nabla \cdot \vec{A}_2 = \frac{I_2 e^{-jkR}}{4\pi j\omega\varepsilon R} \{\frac{1}{R} + jk\}\vec{\ell}_2 \cdot \hat{R} \tag{6}$$

and where $k = 2\pi/\lambda$. R is the distance from the source to the field point in question and R is its associated unit vector. Substituting (4) - (6) into (3) and integrating by parts yields

$$(E_1)_{\text{along } \ell_2} = \frac{1}{I_2\ell_2} \{-j\omega\mu \int_{\ell_1} I_1\vec{A}_2 \cdot \vec{d\ell}_1 + \int_{\ell_1} \phi_2 \frac{dI_1}{d\ell_1} d\ell_1\} \tag{7}$$

where use has been made of the fact that the current vanishes at the ends of the wires.

In employing Harrington's matrix methods to determine the current of a thin-wire antenna a series of triangle expansion functions has been used resulting in a piecewise linear approximation to the current. This is illustrated in Fig. 1. It was mentioned earlier that each wire is thought

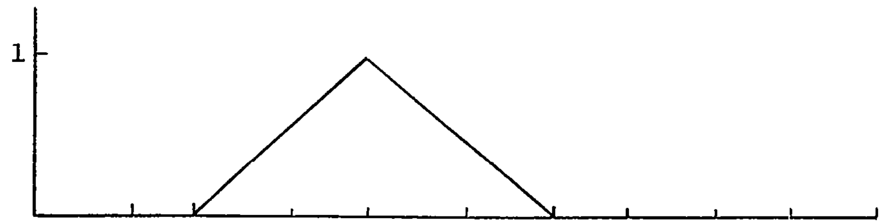

Fig. 1a - Triangle function.

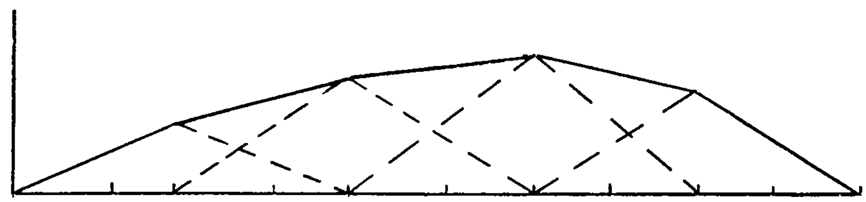

Fig. 1b - Piecewise linear current approximation.

of as a number of short segments connected together, and it is noted that each triangle function extends over four adjacent segments. It is evident then that an even number of segments is required for each wire. The total number of expansion functions for a given problem is denoted by NE. The computer program presented earlier [1] and repeated in the Appendix for convenience calculates amplitudes of these triangles which determine the approximate current distribution. It has been shown through a large number of examples [1,6,7] that current can be determined very accurately in this manner for a wide variety of problems of practical interest.

The expansion of the current for the wire structure is

$$I_1 = \sum_{n=1}^{NE} I_n' T_n \qquad (8)$$

where T_n is the nth triangle expansion function and I_n' is its complex amplitude. Inserting (8) in (7) results in

$$(E_1)_{\text{along } \ell_2} = \frac{1}{I_2 \ell_2} \{-j\omega\mu \sum_{n=1}^{NE} \int_{\ell_1} I_n' T_n \vec{A}_2 \cdot \vec{d\ell}_1 + \sum_{n=1}^{NE} \int_{\ell_1} \phi_2 I_n' \frac{dT_n}{d\ell_1} d\ell_1\} \qquad (9)$$

In order to simplify the integrations required in (9) each triangle expansion function is approximated by four pulse functions $P_1 \rightarrow P_4$ as shown in Fig. 2. The pulses approximating the nth triangle are denoted by $P_{n1} \rightarrow P_{n4}$. Each pulse function exists over only one segment and its amplitude is simply the average of the triangle function over that segment. Note that the segment lengths are not necessarily all the same. Similarly, the derivative term $dT_n/d\ell_n$ is represented by four pulses $Q_1 \rightarrow Q_4$ as shown also in Fig. 2. These representations allow the integrations of (9) to be written as

$$\int_{\ell_1} I'_n T_n \vec{A}_2 \cdot \vec{d\ell}_1 \approx I'_n \sum_{i=1}^{4} P_{ni} \int_{\Delta\ell_{ni}} \vec{A}_2 \cdot \vec{d\ell}_{ni}$$

$$\int_{\ell_1} \phi_2 I'_n \frac{dT_n}{d\ell_1} d\ell_1 \approx I'_n \sum_{i=1}^{4} Q_{ni} \int_{\Delta\ell_{ni}} \phi_2 d\ell_{ni} \qquad (10)$$

Then, using (5) and (6) for $\vec{A}_2$ and ϕ_2, (10) becomes

$$\int_{\ell_1} I'_n T_n \vec{A}_2 \cdot d\vec{\ell}_1 \approx I_2 I'_n \sum_{i=1}^{4} P_{ni} (\vec{\ell}_2 \cdot \hat{\ell}_{ni}) \int_{\Delta\ell_{ni}} \frac{e^{-jkR}}{4\pi R} d\ell_{ni}$$

$$\int_{\ell_1} \phi_2 I'_n \frac{dT_n}{d\ell_1} d\ell_1 \approx \frac{I_2 I'_n}{j\omega\varepsilon} \sum_{i=1}^{4} Q_{ni} (\vec{\ell}_2 \cdot \hat{R}_{ni}) \int_{\Delta\ell_{ni}} \{\frac{e^{-jkR}}{4\pi R^2} + jk \frac{e^{-jkR}}{4\pi R}\} d\ell_{ni} \qquad (11)$$

where $\hat{\ell}_{ni}$ is a unit vector indicating the direction of the segment corresponding to P_{ni}, and $\hat{R}_{ni}$ is a unit vector directed from the center of that segment to the field point in question. Using (11) with (9),

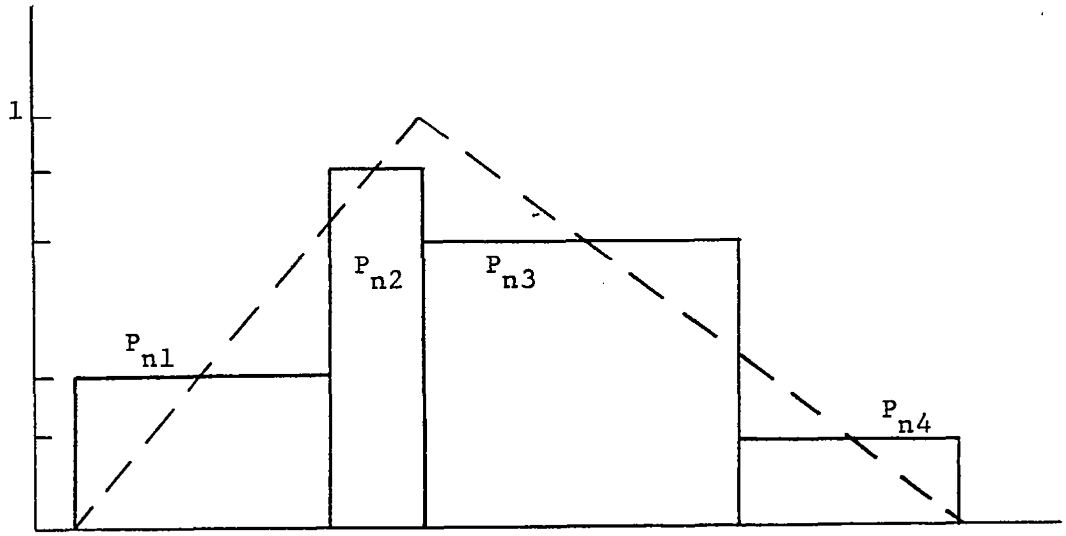

Fig. 2a - Pulses approximating the nth triangle.

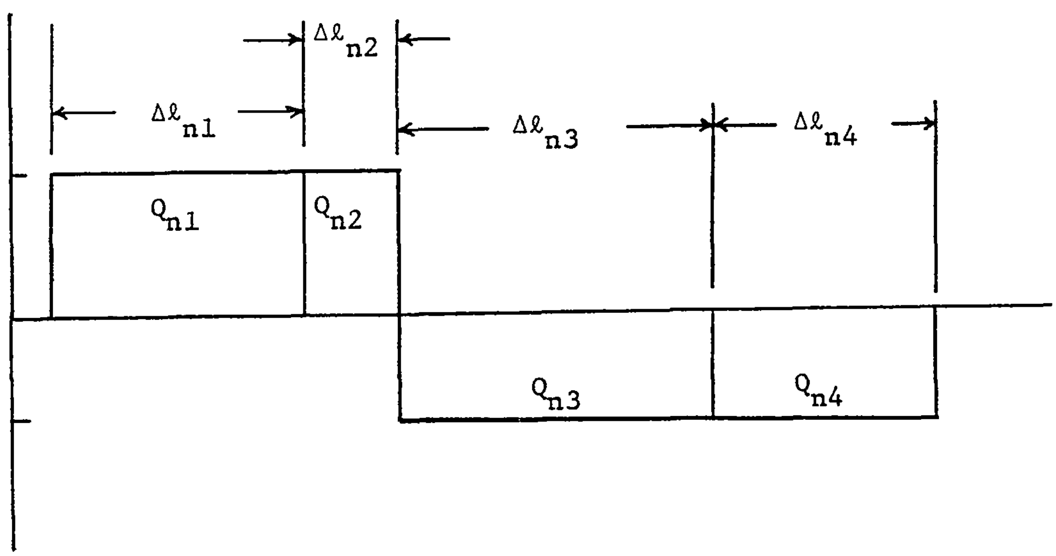

Fig. 2b - Pulses representing the derivative.

$$(E_1)_{\text{along } \ell_2} \approx - j\omega\mu \sum_{n=1}^{NE} I'_n \sum_{i=1}^{4} P_{ni}(\hat{\ell}_2 \cdot \hat{\ell}_{ni})\psi_{ni}$$

$$+ \frac{1}{j\omega\varepsilon} \sum_{n=1}^{NE} I'_n \sum_{i=1}^{4} Q_{ni}(\hat{\ell}_2 \cdot \hat{R}_{ni})(\psi_{ni} + jk\psi'_{ni}) \qquad (12)$$

where $\hat{\ell}_2$ is a unit vector corresponding to $\vec{\ell}_2$ and

$$\psi_{ni} = \int_{\Delta\ell_{ni}} \frac{e^{-jkR}}{4\pi R} \, d\ell_{ni}$$

$$\psi'_{ni} = \int_{\Delta\ell_{ni}} \frac{e^{-jkR}}{4\pi R^2} \, d\ell_{ni} \qquad (13)$$

The function ψ_{ni} can be evaluated easily using formulas provided by Harrington [2,3]. ψ'_{ni} is calculated in essentially the same way except that more terms must be included in the series expansion of the integrand. Thus, (12) can be used to find the component of $\vec{E}_1$ in the direction denoted by $\hat{\ell}_2$. This enables computations of the near field of any given thin-wire structure, subject to the conditions (or restrictions) pointed out in Section I.

III. WIRE CURRENT, EXCITATION, LOADING

It was mentioned earlier that the current distribution of a wire structure is expanded in a series of triangle functions resulting in a piecewise linear current approximation. The computed current is printed out as a sequence of complex numbers, each representing the amplitude of a triangle expansion function. These numbers can be arranged as a column matrix of dimension M where M is the total number of expansion functions used. Hence, the current matrix [I] is

$$[I] = \begin{bmatrix} I'_1 \\ I'_2 \\ \vdots \\ I'_M \end{bmatrix} \tag{14}$$

This is related to the excitation voltages applied to the wire structure by

$$[I] = [Z]^{-1}[V] \tag{15}$$

where [V] is a column matrix of M excitation voltages and [Z] is a generalized impedance matrix. The typical element of [V], say V_i, is the complex excitation voltage applied at a position corresponding to the peak of the ith triangle function. If no excitation is applied at that point then the corresponding element of [V] is zero. It should be recognized that this allows excitation voltages to be applied at any arbitrary points on the wire structure since both the number of expansion functions and the lengths of the individual segments used are selected by the program user. Thus, given the excitation voltages, the current for a given problem is computed using (15). Elements of [Z] are computed from general formulas provided by Harrington [2,3] and programmed earlier [1].

Wire loading is handled by defining a diagonal M×M load impedance matrix $[Z_\ell]$. The typical element $(Z_\ell)_{jj}$ is the complex load impedance in ohms placed at a position corresponding to the peak of the jth triangle function. Of course, if the wire structure is unloaded at that point $(Z_\ell)_{jj}$ is zero. The matrix $[Z_\ell]$ is then simply added to the generalized impedance matrix and the current is given by

$$[I] = [[Z] + [Z_\ell]]^{-1}[V] \tag{16}$$

Then, once the current is known the near-zone fields at points of interest can be computed using the procedures outlined in Section II.

IV. DESCRIPTION OF THE PROGRAM

Subject to the restriction pointed out in Section I the computer program presented in the Appendix is suitable for calculating the components of the electric field vector at any given point in the near field of a thin-wire antenna. The program is written in Fortran IV for use with an IBM 360/50 computer. Complex variables are used to simplify the programming and use is made of a common region to conserve memory space. Sample input and output data are included in the Appendix along with the program listing.

This program is limited to problems involving thin wires with lumped sources and/or lumped loads at wire positions corresponding to the peaks of triangle expansion functions. The maximum number of wires that can be handled is four. The maximum number of expansion functions for any one wire is fifteen. For antennas having more wires or longer wires requiring additional expansion functions to obtain a good current approximation, the dimension statements should be changed. All input data are provided for in the main program, as there are no read statements in the subroutines. All FORMAT statements are placed at the end of the main program.

In this section information is given which should enable the reader to apply the program to specific problems of interest. Particular attention is given to required input data.

DATA INPUT

The first data statement reads in the wavelength in meters, denoted by WAVE in the computer program.

The second data statement reads in the total number of wires in the problem geometry. This is denoted by NWIRE in the program.

The remaining read statements are included in DO Loop 550. This loop iterates a total of NWIRE times. Hence the set of read statements included also executes NWIRE times. Therefore, these five read statements correspond to NWIRE sets of data cards, with each set corresponding to one wire of the total in the problem geometry.

The third read statement reads in BA(NW),NS(NW), NF(NW), and NL(NW) where NW is the index of DO Loop 550. BA(NW) is the wire radius in wavelengths of the NWth wire. NS(NW) is the number of segments making up the NWth wire. (NS should be an even number.) NF(NW) is the number of feed points on the NWth wire; i.e., the number of segments to which excitation voltages are applied. (If no excitation is applied on the wire, NF(NW) = 1 and the source is specified as a source with zero voltage.) NL(NW) is the number of loads on the NWth wire. (If no loads are used on the wire then NL(NW) = 1 and the load is specified as ZL(1,1) = (0.0, 0.0), a load with zero impedance.)

The fourth read statement reads in the positions of the feed points on the NWth wire. For example, if excitation voltages are applied to the peaks of the third and eighth triangle functions on the NWth wire then IF(NW,1) = 3 and IF(NW,2) = 8.

The fifth read statement reads in the applied excitation voltages at the feed points which are specified by the fourth data statement as discussed above.

The sixth read statement provides the positions of the loads along the NWth wire. Thus if the first load on the NWth wire is applied at the peak of the fifth triangle function, the second to the eighth, etc., then LP(NW,1) = 5, LP(NW,2) = 8, and so on.

The seventh read statement reads in the load impedances to be applied on the NWth wire at the points specified by the sixth data statement. These are written as complex numbers, in ohms.

The next task is to specify the geometry. In the first place, all antennas including those with junctions are treated as combinations of open-ended wires. Hence, the number of expansion functions on the NWth wire can be evaluated as

$$NE(NW) = NS(NW)/2 - 1 \tag{17}$$

and the number of points on the axis of the wire which should be specified can be evaluated as

$$NP(NW) = NS(NW) + 1 \qquad (18)$$

[X(1,NW,I),X(2,NW,I),X(3,NW,I)] corresponds to the Cartesian coordinates of the point $P_{NW,I}$ which is the ith point on the NWth wire. The point specifying the geometry of a wire should begin at one end and proceed with consecutive numbering to the last point at the other end of the wire. These points can either be specified by reading in their coordinates or by calculating them with a generating function. In the sample program printout in the Appendix DO Loops 1510 and 1520 are used to specify points on the axis of a single straight wire. These, of course, could just as well be read in point by point as data input. Generating functions for certain other commonly encountered configurations are included in an earlier report [1].

DO Loop 560 obtains XX, XD, and TLEN, where the numbers XX are the coordinates of the center points of the segments, XD are the direction numbers of the segments, and TLEN are the lengths of the segments.

The generalized impedance matrix [Z] is computed using subroutine CALZ. Modification of the matrix [Z] to include the effects of loads on the wires is performed by subroutine CALZL. The generalized admittance matrix [Y] is obtained by inverting the matrix [Z] using subroutine LINEQ. (Because we store [Y] and [Z] in the same locations, the admittance matrix is still named [Z] in the program.) The generalized voltage matrix [V] (denoted by [U] in the program) is evaluated using subroutine BIGV. Once the matrices $[Z]^{-1}$ and [V] are available, the generalized current matrix [I] can be obtained by performing the matrix product in subroutine CRNT. DO Loop 30 computes the magnitude and phase of the current and prints them out along with the real and imaginary parts. Each complex number, of course, represents the amplitude of the corresponding triangle expansion function.

Once the current is known all that remains is to specify points at which the near-zone field is to be evaluated and also the particular vector components to be computed. With regard to the latter suppose vector components denoted by unit vectors $\hat{u}_1$, $\hat{u}_2$, $\hat{u}_3$ are desired. This information is read in using a 3×3 matrix YD defined as

$$YD = \begin{bmatrix} \hat{u}_x \cdot \hat{u}_1 & \hat{u}_x \cdot \hat{u}_2 & \hat{u}_x \cdot \hat{u}_3 \\ \hat{u}_y \cdot \hat{u}_1 & \hat{u}_y \cdot \hat{u}_2 & \hat{u}_y \cdot \hat{u}_3 \\ \hat{u}_z \cdot \hat{u}_1 & \hat{u}_z \cdot \hat{u}_2 & \hat{u}_z \cdot \hat{u}_3 \end{bmatrix} \qquad (19)$$

Thus, if it is desired to compute the x,y,z components of the electric field at given points then YD is simply a unit matrix. On the other hand if spherical components corresponding to unit vectors u_r, $\hat{u}_\theta$, $\hat{u}_\phi$ are of interest then

$$YD = \begin{bmatrix} \sin\theta\cos\phi & \cos\theta\cos\phi & -\sin\phi \\ \sin\theta\sin\phi & \cos\theta\sin\phi & \cos\phi \\ \cos\theta & -\sin\theta & 0 \end{bmatrix} \qquad (20)$$

Elements of YD are read in with statements 446-454 in the printout shown in the Appendix.

Subroutine ENEAR is used to calculate the near field at given points of interest. The subroutine is called once for each point specified and uses (12) to compute the three vector components desired as described above. The x,y,z coordinates of a given point for which the field is to be computed are labeled YY(1), YY(2), and YY(3) respectively in the program, and these, of course, must be provided by the user. If the field is to be calculated at more than one point then YY(1), YY(2), and YY(3) must be changed for each new point considered. This is done using DO Loop 71 in the program and sample output of the Appendix. Finally, for each point considered the real and imaginary parts, magnitude, and phase of each component of the electric field vector are printed out.

V. EXAMPLES

As an example consider a centerfed, straight cylindrical antenna that is two meters long and driven by an independent voltage source of two volts. Suppose the wavelength is $4\pi/3$ meters and that the wire radius is constant at 0.00325λ. (This is equivalent to the base-driven monopole studied by Harrison et al. [8].) Suppose further that the wire is unloaded and that a total of 28 segments corresponding to 13 current expansion functions are to be used in the analysis.

The required data input for this problem is as follows:

WAVE = 4.14879 (wavelength in meters)	1st statement
NWIRE = 1 (number of wires)	2nd statement
BA(1) = 0.00325 (radius of first wire in wavelengths) NS(1) = 28 (number of segments - first wire) NF(1) = 1 (number of feed points - first wire) NL(1) = 1 (number of load positions - first wire)	3rd statement
IF(1,1) = 7 (first feed point on the first wire is located at the peak of the 7th triangle)	4th statement
V(1,1) = (2.0, 0.0) (excitation applied at the first feed point of the first wire is 2.0 +j0.0)	5th statement
LP(1,1) = 1 (the first load position on the first wire corresponds to the peak of the first triangle)	6th statement
ZL(1,1) = (0.0, 0.0) (load impedance applied at the first load position of the first wire is 0.0 +j0.0)	7th statement

The problem geometry is read in by specifying points along the axis of the wire using DO Loop 1520 and DO Loop 1510. A total of 29 points are used to define the 28 segments making up the wire. In this example all segments are of equal length. Of course, if a generating function is not used to define the problem geometry the axial points can be read in one by one as data input.

Suppose the x,y,z components of the near-zone electric field are of interest. Then the YD matrix is simply a 3×3 unit matrix and is given in statements 446-454 in the program of the Appendix. Finally, DO Loop 71 is used to specify points in space where the near-zone electric field is to be determined. In order to insure accurate results the nearest point, of course, cannot be closer than $\Delta\ell = 2/28$ meters from the wire surface. In this case the points examined are in the planes defined by z=0, z=0.5, and z=1.0 (where the wire is z-directed with the feed point at z=0) and at distances from the wire given by x=0 and y=0.2, 0.6, 1.0, 1.4 meters. Results are included in the Appendix and these compare quite favorably with those derived earlier by Harrison et al. [8] for $\beta h = 1.5$.

As a second example consider a circular loop antenna located in the xy plane and centered at the origin as shown in Fig. 3. The wire radius is 0.00106λ and the loop radius is $b = \lambda/2\pi$. The wavelength is 0.5 meter and the excitation is a unit voltage at $\phi' = 0$. The problem is treated as an open wire with two segments overlapping at the ends of the wire as explained in the previous report [1]. A total of 30 segments are used, corresponding to 14 current expansion functions. The wire is unloaded and the excitation is applied at a wire position corresponding to the peak of the 14th triangle ($\phi' = 0$).

Input and output data for this problem are included in the Appendix. The problem geometry is defined by specifying positions for a total of 31 points using DO Loops 1510 and 1511. Rectangular near-field vector components are called for so YD is a unit matrix as before. Points at which the field is to be calculated are read in using DO Loop 71. These are shown in the printout of the Appendix to be along the x-axis at x=0.0, 0.02, 0.06, 0.14, 0.30, and 0.62.

Examples involving use of more than one wire, bent and loaded wires, and wire junctions are available elsewhere [1]. Data for these can be used directly with the program presented here. The only additional input required are the YD matrix and the locations of points where near-field computations are to be made.

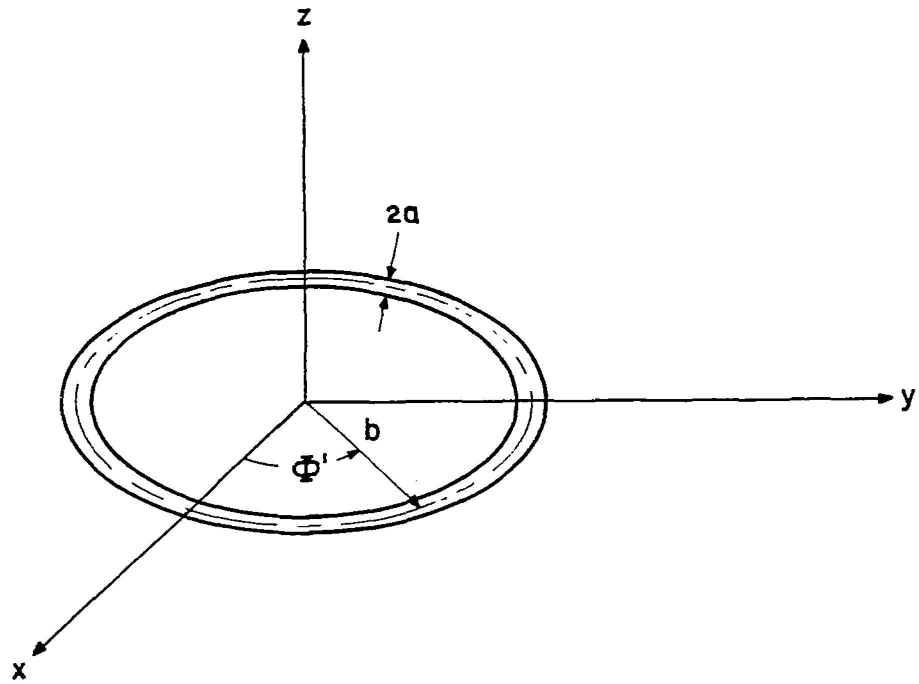

Fig. 3a - Circular loop and coordinate system.

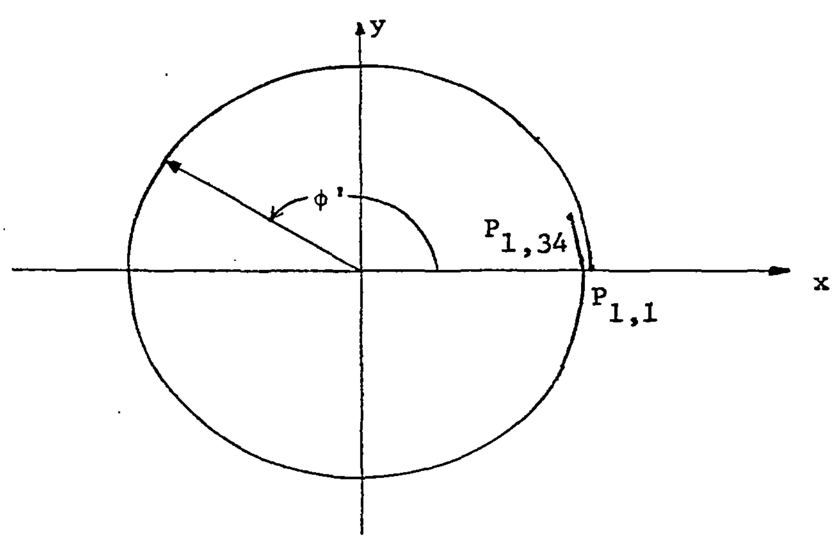

Fig. 3b - Open wire with two segments overlapping.

VI. CONCLUSION

A user-oriented computer program has been presented and described for calculating the near fields of thin wire antennas. The program is an extension of one presented earlier for computing current distributions and far-field patterns for arbitrary configurations of bent wires with junctions. Results are valid for a given point in space if the point is at least a distance $\Delta\ell$ from the nearest wire surface, where $\Delta\ell$ denotes the length of the longest subsection or segment used in the analysis. The wires of a given problem can be excited or loaded at arbitrary points along their lengths, and no unrealistic assumptions are necessary regarding their current distributions. Finally, mutual coupling is taken completely into account with each step of the analysis procedure.

In this report instructions for using the program were given with particular attention devoted to required data input. Two examples were included to illustrate its use.

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VIII. APPENDIX

This program is suitable for computing near fields of thin wires with excitations represented by lumped voltage sources at the peaks of the triangle functions and loading represented by lumped loads, also at the peaks of the triangle functions. The maximum number of wires that can be handled here is four. The maximum number of expansion functions for any wire is fifteen. Subroutines are listed first. The sample input and output data listed here correspond to the analysis of example one. The problem geometry is read in with instructions 402-415. The YD matrix is provided through instructions 446-454 and field points of interest are specified with statements 456-480. The program is described in Section IV.

```
 1        SUBROUTINE ENEAR (WAVE,NWIRE,A,NE,C,NEP,YY,YD)
 2        COMPLEX PSI(4),PSI1(4),CI,RT,EX(3,60),C(60),E(3),Z1,Z2
         1,CMPLX,HOLD1,HOLD2,CEXP
 3        DIMENSION YY(3),YD(3,3),NE(NWIRE),YDD(3,4),XDD(3,4),RX(3),A(4),
         1P(4),Q(4),XD(3,4,32),XX(3,4,32),TLEN(4,32)
 4        COMMON /CDA/XX,XD,TLEN /CDE/F
 5        CI=(0.,1.)
 6        PI=3.14159265
 7        BETA=2.0*PI/WAVE
 8        EPSLN=8.854E-12
 9        OMEG=2.0*PI*2.997923E8/WAVE
10        XMU=4.0E-7*PI
11        N=0
12        DO 10 NWS=1,NWIRE
13        NENWS=NE(NWS)
14        DO 10 NES=1,NENWS
15        N=N+1
16        IF (NES.EQ.1) GO TO 11
17        PSI(1)=PSI(3)
18        PSI(2)=PSI(4)
19        PSI1(1)=PSI1(3)
20        PSI1(2)=PSI1(4)
21        DO 191 I=1,3
22        XDD(I,1)=XDD(I,3)
23        XDD(I,2)=XDD(I,4)
24        YDD(I,1)=YDD(I,3)
25        YDD(I,2)=YDD(I,4)
26    191 CONTINUE
27        KK=3
28        GO TO 18
29     11 KK=1
30     18 CONTINUE
31        DO 60 K=KK,4
```

```
      NESK=2*NES-2+K
      R=0.
      DO 15 J=1,3
      RX(J)=XX(J,NWS,NESK)-YY(J)
   15 R=R+RX(J)**2
      R=SQRT(R)
      DO 192 I=1,3
      XDD(I,K)=0.
      YDD(I,K) = 0.
      DO 100 J=1,3
      XDD(I,K)=XDD(I,K)+YD(J,I)*RX(J)/R
      YDD(I,K) = YDD(I,K) + XD(J,NWS,NESK)*YD(J,I)
  100 CONTINUE
  192 CONTINUE
      ALP=TLEN(NWS,NESK)/2.
      ZZ=0
      DO 33 J=1,3
   33 ZZ=ZZ+RX(J)*XD(J,NWS,NESK)/(2.*ALP)
      ZZ=ABS(ZZ)
      AL=SQRT(ABS(R**2-ZZ**2))
      IF(R.GE.10.*ALP) GO TO 31
      RT=COS(-BETA*R)+CI*SIN(-BETA*R)
      ZA=ZZ+ALP
      ZAM=ZZ-ALP
      SZA=SQRT(AL**2+ZA**2)
      SZAM=SQRT(AL**2+ZAM**2)
      IF(ZZ.GT.ALP) GO TO 41
      AI1=ALOG((ZA+SZA)*(-ZAM+SZAM)/AL**2)
      GO TO 42
   41 AI1=ALOG((ZA+SZA)/(ZAM+SZAM))
   42 AI2=2.*ALP
      AI3=(ZA*SZA-ZAM*SZAM+AL**2*AI1)/2.
      AI4=AI2*AL**2+(2.*ALP**3+6.*ALP*ZZ**2)/3.
      PSIA=AI1-BETA**2/2.*(AI3-2.*R*AI2+R**2*AI1)
      PSIB=-BETA*(AI2-R*AI1)+BETA**3/6.*(AI4-3.0*R*AI3+3.*R**2*AI2-R**3
     1*AI1)
      PSI(K)=RT/(8*PI*ALP)*CMPLX(PSIA,PSIB)
      R2=R**2
      R3=R**3
      R4=R**4
      ARG=2.*AL* ALP/(R**2-ALP**2)
      AI0=ATAN(ARG)/AL
      PSIC=AI0-BETA**2/2.*(AI2-2.*R*AI1+R2*AI0)+BETA**4/24.*(AI4-4.*R
     1*AI3 +6.*R2*AI2 -4.*R3*AI1 + R4*AI0))
      PSID=-BETA*(AI1-R*AI0) + BETA**3/6.*(AI3-3.*R*AI2+3.*R2*AI1
     1-R3*AI0)
      PSI1(K)=RT/(8*PI*ALP)*CMPLX(PSIC,PSID) +CI*BETA*PSI(K)
      GO TO 59
   31 XKD=BETA*ALP
      RT=COS(-BETA*R)+CI*SIN(-BETA*R)
      ZR=ZZ/R
      DR=ALP/R
      ZR2=ZR**2
      ZR4=ZR2**2
```

```
      DR2=DR**2
      H=(-1.0+3.0*ZR2)/6.0
      H1=(3.0-30.0*ZR2+35.0*ZR4)/40.0
      A0=1.0+H*DR2+H1*DR2**2
      A1=H*DR+H1*DR2*DR
      A2=-ZR2/6.0-DR2/40.0*(1.0-12.0*ZR2+15.0*ZR4)
      A3=DR/60.0*(3.0*ZR2-5.0*ZR4)
      A4=ZR4/120.0
      PSIA=A0+XKD**2*A2+XKD**4*A4
      PSIB=XKD*A1+XKD**3*A3
      PSI(K)=RT/ (4.*PI*R)*CMPLX(PSIA,PSIB)
      B0=1.+DR2*(-1.+4.*ZR2)/3.+.2*DR2**2*(1.-12.*ZR2+16.*ZR4)
      B1=DR*(-1.+5.*ZR2)/6.+.025*(5.-66.*ZR2+93.*ZR4)*DR**3
      B2=-ZR2/6.-.025*DR2*(1.-18.*ZR2+29.*ZR4)
      B3=DR/60.*(3.*ZR2-7.*ZR4)
      B4=A4
      PSIC=B0+XKD**2*B2+XKD**4*B4
      PSID=XKD*B1+XKD**3*B3
      PSI1(K)=RT/(4.*PI*R**2)*CMPLX(PSIC,PSID)+CI*BETA*PSI(K)
   59 CONTINUE
   60 CONTINUE
      M=2*NES-2
      ABCA=TLEN(NWS,2*NES-1)
      ABCB=TLEN(NWS,2*NES)
      ABCC=TLEN(NWS,2*NES+1)
      ABCD=TLEN(NWS,2*NES+2)
      P(1)  =  1/2.*ABCA/(ABCA+ABCB)
      P(2)  =  (ABCA+1/2.*ABCB)/(ABCA+ABCB)
      P(3)  =  (1/2.*ABCC+ABCD)/(ABCC+ABCD)
      P(4)  =1/2.*ABCD/(ABCC+ABCD)
      Q(1)  =  1./(ABCA+ABCB)
      Q(2)=Q(1)
      Q(3)  =-1./(ABCC+ABCD)
      Q(4)=Q(3)
      DO 190 I=1,3
      Z1=0
      Z2=0
      DO 193 J=1,4
      Z1=Z1+P(J)*PSI(J)*YDD(I,J)
  193 Z2=Z2+Q(J)*PSI1(J)*XDD(I,J)*TLEN(NWS,M+J)
      EX(I,N)=-CI*OMEG*XMU*Z1*C(N)  -CI/(OMEG*EPSLN)*Z2*C(N)
  190 CONTINUE
   10 CONTINUE
      DO 70 I=1,3
      E(I)=(0.,0.)
      DO 70 N=1,NEP
      E(I)=E(I) + EX(I,N)
   70 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE CALZ(   WAVE,NWIRE,A,NE,NN)
      COMPLEX Z(60,60),Z4(4,15,4,15),PSI(4,32,4)
     1,RT, CEXP, CI, CMPLX, HOLD1, HOLD2
      DIMENSION  A(NWIRE),NE(NWIRE),NN(NWIRE),XX(3,4,32),
     1XD(3,4,32),  TLEN(4,32),  R(4,32,4),RX(3,4,32,4),
     2ZZ(4,32,4),  XDD(4,32,4),ALP(4),C(4),D(4),P(4),Q(4)
      COMMON /COA/ XX,XD,TLEN /COB/ Z
      CI=(0.0,1.0)
      PI=3.14159265
      BETA=2.0*PI/WAVE
      EPSLN = 8.854E-12
      OMEG = 2.0*PI*2.997928E8/WAVE
      XMU=4.0E-7*PI
      DO 10 NWS=1,NWIRE
      NENWS=NE(NWS)
      DO 10 NES=1,NENWS
C     NWS= THE NUMBER OF THE WIRE (SOURCE)
C     NWF= THE NUMBER OF THE WIRE (FIELD POINT)
C     NES = THE NUMBER OF THE EXPENSION FUNCTION (SOURCE)
C     NEF = THE NUMBER OF THE EXPENSION FUNCTION (FIELD POINT)
C     NSS = THE NUMBER OF THE  SEGMENT (SOURCE)
C     NSF = THE NUMBER OF THE  SEGMENT (FIELD POINT)
      IF(NES.EQ.1) GO TO 11
      DO 17 NWF=1,NWIRE
      NNNWF=NN(NWF)
      DO 17 NSF=1,NNNWF
      XDD(NWF,NSF,1) = XDD(NWF,NSF,3)
      XDD(NWF,NSF,2) = XDD(NWF,NSF,4)
      PSI(NWF,NSF,1) = PSI(NWF,NSF,3)
   17 PSI(NWF,NSF,2) = PSI(NWF,NSF,4)
      KK = 3
      GO TO 18
   11 KK=1
   18 CONTINUE
      DO 60 K =KK,4
      NESK=2*NES-2+K
      DO 60 NWF=1,NWIRE
      NNNWF=NN(NWF)
      DO 60 NSF=1,NNNWF
      R(NWF,NSF,K) =0.
      DO 15 J=1,3
      RX(J,NWF,NSF,K) =   XX(J,NWF,NSF) - XX(J,NWS,NESK)
   15 R(NWF,NSF,K) = R(NWF,NSF,K) +      RX(J,NWF,NSF,K)**2
      R(NWF,NSF,K) = SQRT(R(NWF,NSF,K))
      ALP(K) = TLEN(NWS,NESK)/2.
      ZZ(NWF,NSF,K) =0.
      DO 33 J=1,3
   33 ZZ(NWF,NSF,K) = ZZ(NWF,NSF,K)+RX(J,NWF,NSF,K)*XD(J,NWS,NESK)/
     1(2.*ALP(K))
      ZZ(NWF,NSF,K) = ABS(ZZ(NWF,NSF,K))
      XDD(NWF,NSF,K)=0.
      DO 65 J=1,3
   65 XDD(NWF,NSF,K) = XDD(NWF,NSF,K)+XD(J,NWS,NESK     )*XD(J,NWF,NSF)
      AL = SQRT(ABS(R(NWF,NSF,K)**2-ZZ(NWF,NSF,K)**2))
```

```
      AL=SQRT(AL**2+A(NWS)**2)
      IF  (R(NWF,NSF,K).GE.10.*ALP(K))  GO TO 31
      R(NWF,NSF,K) = SQRT(R(NWF,NSF,K)**2+A(NWS)**2)
      RT = COS(-BETA*R(NWF,NSF,K)) + CI*SIN(-BETA*R(NWF,NSF,K))
      ZA = ZZ(NWF,NSF,K) + ALP(K)
      ZAM = ZZ(NWF,NSF,K)-ALP(K)
      SZA=SQRT(AL**2+ZA**2)
      SZAM=SQRT(AL**2+ZAM**2)
      IF (ZZ(NWF,NSF,K).GT.ALP(K)) GO TO 41
      AI1=ALOG((ZA+SZA)*(-ZAM+SZAM)/AL**2)
      GO TO 42
   41 AI1=ALOG((ZA+SZA)/(ZAM+SZAM))
   42 AI2=2.*ALP(   K)
      AI3=(ZA*SZA-ZAM*SZAM+AL**2*AI1)/2
      AI4=AI2*AL**2+(2.*ALP(   K)**3+6.*ALP(   K)*ZZ(NWF,NSF,K)**2)/3.
      PSI1=AI1-BETA**2/2.*(AI3-2.*R(NWF,NSF,K)*AI2+R(NWF,NSF,K)**2*AI1)
      PSI2= -BETA*(AI2-R(NWF,NSF,K)*AI1)+BETA**3/6.*(AI4-3.*R(NWF,NSF,K)
     1*AI3+3.*R(NWF,NSF,K)**2*AI2-R(NWF,NSF,K)**3*AI1)
      PSI(NWF,NSF,K) = RT/(8*PI*ALP(K))*CMPLX(PSI1,PSI2)
      GO TO 59
   31 XKD=BETA*ALP(   K)
      RT = COS(-BETA*R(NWF,NSF,K)) + CI*SIN(-BETA*R(NWF,NSF,K))
      ZR=ZZ(NWF,NSF,K)/R(NWF,NSF,K)
      DR=ALP(K)/R(NWF,NSF,K)
      ZR2=ZR**2
      ZR4=ZR2**2
      DR2=DR**2
      H=(-1.0+3.0*ZR2)/6.0
      H1=(3.0-30.0*ZR2+35.0*ZR4)/40.0
      A0=1.0+H*DR2+H1*DR2**2
      A1=H*DR+H1*DR2*DR
      A2=-ZR2/6.0-DR2/40.0*(1.0-12.0*ZR2+15.0*ZR4)
      A3=DR/60.0*(3.0*ZR2-5.0*ZR4)
      A4=ZR4/120.0
      PSI1=A0+XKD**2*A2+XKD**4*A4
      PSI2=XKD*A1+XKD**3*A3
      PSI(NWF,NSF,K) = RT/(4*PI*R(NWF,NSF,K))*CMPLX(PSI1,PSI2)
   59 CONTINUE
   60 CONTINUE
      ABCA=TLEN(NWS,2*NES-1)
      ABCB=TLEN(NWS,2*NES)
      ABCC=TLEN(NWS,2*NES+1)
      ABCD=TLEN(NWS,2*NES+2)
      C(1) = 1/2.*ABCA/(ABCA+ABCB)
      C(2) = (ABCA+1/2.*ABCB)/(ABCA+ABCB)
      C(3) = (1/2.*ABCC+ABCD)/(ABCC+ABCD)
      C(4) =1/2.*ABCD/(ABCC+ABCD)
      D(1) = 1./(ABCA+ABCB)
      D(2) =D(1)
      D(3) =-1./(ABCC+ABCD)
      D(4) =D(3)
      DO 10 NWF=1,NWIRE
      NENWF=NE(NWF)
      DO 10 NEF=1,NENWF
      ABCA=TLEN(NWF,2*NEF-1)
```

```
      ABCB=TLEN(NWF,2*NEF)
      ABCC=TLEN(NWF,2*NEF+1)
      ABCD=TLEN(NWF,2*NEF+2)
      P(1) = 1/2.*ABCA/(ABCA+ABCB)
      P(2) = (ABCA+1/2.*ABCB)/(ABCA+ABCB)
      P(3) = (1/2.*ABCC+ABCD)/(ABCC+ABCD)
      P(4) =1/2.*ABCD/(ABCC+ABCD)
      Q(1) = 1./(ABCA+ABCB)
      Q(2) = Q(1)
      Q(3) =-1./(ABCC+ABCD)
      Q(4) =Q(3)
      Z4(NWF,NEF,NWS,NES) = (0.,0.)
      DO 70 I=1,4
      DO 70 K=1,4
      L=2*NEF-2+I
   70 Z4(NWF,NEF,NWS,NES) = Z4(NWF,NEF,NWS,NES) + CI*OMEG*XMU*C(K)*P(I)*
     1XDD(NWF,L,K)*PSI(NWF,L,K)+1./(CI*OMEG*EPSLN)*D(K)*Q(I)*PSI(NWF,L,
     2K)*TLEN(NWS,2*NES-2+K)*TLEN(NWF,L)
   10 CONTINUE
      NUF =0
      DO 90 NWF =1,NWIRE
      NENWF=NE(NWF)
      DO 90 NEF=1,NENWF
      NUF = NUF +1
      NUS = 0
      DO 90 NWS=1,NWIRE
      NENWS=NE(NWS)
      DO 90 NES=1,NENWS
      NUS = NUS+1
   90 Z(NUF,NUS) = Z4(NWF,NEF,NWS,NES)
      RETURN
      END
C     ////////////////////////////////////////////////////////////////////////

      SUBROUTINE CALZL(NL,NE,NWIRE)
C     TO ADD THE IMPEDANCE MATRIX ZL TO Z TO FORM THE TOTAL IMPEDANCE
C     MATRIX
C     Z=THE IMPEDANCE MATRIX
C     ZL = LOADS
C     NE IS NUMBER OF EXPENSION FUNCTIONS
C     NWIRE = NUMBER OF WIRES
      COMPLEX Z(60,60),ZL(4,32)
      DIMENSION LP(4,32)          ,NL(NWIRE),NE(NWIRE)
      COMMON /COB/ Z /COC/ZL,LP
      JJ=0
      DO 20 K=1,NWIRE
      IF (K.EQ.1) GO TO 11
      JJ=JJ+NE(K-1)
   11 CONTINUE
      NLK=NL(K)
      DO 20 I=1,NLK
      J=JJ+LP(K,I)
   20 Z(J,J)=Z(J,J)+ZL(K,I)
      RETURN
      END
```

```
      SUBROUTINE LINEQ(N,   L,M)
C     USE GAUSS-JORDAN METHOD
C     N=ORDER OF THE MATRIX
C     A=THE INPUT AND OUTPUT MATRIX
C     L,M=WORKING VECTOR
      COMPLEX     A(60,60),BIGA,HOLD
      DIMENSION L(N),M(N)
      COMMON /CUB/ A
      DO 80 K=1,N
      L(K)=K
      M(K)=K
      BIGA=A(K,K)
      DO 20 J=K,N
      DO 20 I=K,N
   10 IF (CABS(BIGA)-CABS(A(I,J))) 15,19,19
   15 BIGA=A(I,J)
      L(K)=I
      M(K)=J
   19 CONTINUE
   20 CONTINUE
      J=L(K)
      IF(J-K) 35,35,25
   25 CONTINUE
      DO 30 I=1,N
      HOLD=-A(K,I)
      A(K,I)=A(J,I)
   30 A(J,I)=HOLD
   35 I=M(K)
      IF(I-K) 45,45,38
   38 CONTINUE
      DO 40 J=1,N
      HOLD=-A(J,K)
      A(J,K)=A(J,I)
   40 A(J,I)=HOLD
   45 CONTINUE
      DO 55 I=1,N
      IF(I-K) 50,55,50
   50 A(I,K)=A(I,K)/(-BIGA)
   55 CONTINUE
      DO 65 I=1,N
      DO 65 J=1,N
      IF(I-K) 60,64,60
   60 IF(J-K) 62,64,62
   62 A(I,J)=A(I,K)*A(K,J)+A(I,J)
   64 CONTINUE
   65 CONTINUE
      DO 75 J=1,N
      IF(J-K) 70,75,70
   70 A(K,J)=A(K,J)/BIGA
   75 CONTINUE
      A(K,K)=1./BIGA
   80 CONTINUE
      K=N
  100 K=K-1
      IF(K) 150,150,105
  105 I=L(K)
      IF(I-K) 120,120,108
  108 CONTINUE
```

```
      DO 110 J=1,N
      HOLD=A(J,K)
      A(J,K)=-A(J,I)
  110 A(J,I)=HOLD
  120 J=M(K)
      IF(J-K) 100,100,125
  125 CONTINUE
      DO 130 I=1,N
      HOLD=A(K,I)
      A(K,I)=-A(J,I)
  130 A(J,I)=HOLD
      GO TO 100
  150 RETURN
      END
C     ///////////////////////////////////////////////////////////////////

      SUBROUTINE BIGV(U,NF,NWIRE,NE,NEP)
      COMPLEX V(4,32),U(NEP)
      DIMENSION IF(4,32)        ,NF(NWIRE),NE(NWIRE)
      COMMON /CUD/V,IF
      DO 5 I=1,NEP
    5 U(I) = (0.,0.)
      JJ=0
      DO 10 K=1,NWIRE
      IF(K.EQ.1) GO TO 11
      JJ=JJ+NE(K-1)
   11 CONTINUE
      NFK=NF(K)
      DO 10 I=1,NFK
      J=JJ+IF(K,I)
   10 U(J) = V(K,I)
      RETURN
      END
C     ///////////////////////////////////////////////////////////////////

      SUBROUTINE CRNT(U,  C,NS)
C     MULTIPLY A MATRIX BY A VECTOR
C     U = THE INPUT VECTOR
C     Y = THE INPUT MATRIX
C     C = THE RESULT VECTOR
C     NS = ORDER OF MATRIX
      COMPLEX U(NS),Y(50,60),C(NS)
      COMMON /CUB/ Y
      DO 5 I=1,NS
      C(I)=(0. ,0.)
      DO 5 L=1,NS
    5 C(I)=C(I)+Y(I,L)*U(L)
      RETURN
      END
C     ///////////////////////////////////////////////////////////////////
```

```
C       MAIN PROGRAM            MMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMM
        COMPLEX ZL(4,32),V( 4,32),Z (60,60),U( 60),C(60),
       1E(3), ZIN,CONJG,CI,YIN,CAI,CBI,CC
        DIMENSION BA(12),A(12),NS(12),  NF(12), NL(12), NCLOSE(12),
       1X(3,4,32),NE(12),NP(12),NN(12),IF(4,32),LP(4,32),XX(3,4,32),
       2XD(3,4,32),TLEN(4,32),LMNOP(60),MMNOP(60),
       3YY(3),YD(3,3)
        COMMON /COA/XX,XD,TLEN /COB/Z /COC/ZL,LP /COD/V,IF /COE/E
        PI =3.14159265
        XMU = 4.0E-7*PI
        EPSLN = 8.854E-12
        CI = (0.,1.)
    100 READ (1,2,  END=500)  WAVE
        WRITE (3,11) WAVE
        OMEG=2.997928E8/WAVE*2.*PI
        BETA = 2.*PI/WAVE
        READ (1,3) NWIRE
        WRITE (3,12) NWIRE
        WRITE (3,151)
        DO 550 NW=1,NWIRE
        WRITE (3,13) NW
        READ (1,1) BA(NW),NS(NW),NF(NW),NL(NW)
        WRITE (3,5) BA(NW),NS(NW),NF(NW),NL(NW)
        NFNW=NF(NW)
        READ(1,3) (IF(NW,I),I=1,NFNW  )
        WRITE(3,6) (IF(NW,I),I=1,NFNW  )
        READ   (1,4) (V(NW,I),I=1,NFNW  )
        WRITE(3,7)   (V(NW,I),I=1,NFNW  )
        NLNW =NL(NW)
        READ (1,3)  (LP(NW,I),I=1,NLNW  )
        WRITE (3,8) (LP(NW,I),I=1,NLNW  )
        READ (1,4) (ZL(NW,I),I=1,NLNW)
        WRITE(3,9)  (ZL(NW,I),I=1,NLNW  )
        WRITE (3,152)
        NE(NW) = NS(NW)/2-1
        NP(NW) =NS(NW) +1
        NN(NW) = 2*NE(NW)+2
        NPNW=NP(NW)
        DO 1520 I=1,NPNW
        X(1,NW,I)=0.
        X(2,NW,I)=0.
   1520 CONTINUE
        X(3,NW,15) =0.
        DO 1510 I=1,14
        XI = I
        L1=15+I
        L2=15-I
        CORD=0.07142857*XI
        X(3,1 ,L1)=CORD
        X(3,1 ,L2)=(-1.)*CORD
   1510 CONTINUE
        WRITE (3,310)
        WRITE(3,300) ((X(J,NW,I),J=1,3),I=1,NPNW)
        WRITE (3,152)
    550 CONTINUE
```

```
      DO 560 NW=1,NWIRE
      NNNW=NN(NW)
      DO 15 I=1,NNNW
      DO 15 J=1,3
      XX(J,NW,I) = (X(J,NW,I)+X(J,NW,I+1))/2.
   15 XD(J,NW,I)=X(J,NW,I+1)-X(J,NW,I)
      DO 20 I=1,NNNW
   20 TLEN(NW,I) = SQRT(XD(1,NW,I)**2+XD(2,NW,I)**2+XD(3,NW,I)**2)
      A(NW) = BA(NW)*WAVE
  560 CONTINUE
      WRITE(3,151)
      NEP=0
      DO 28 NW=1,NWIRE
   28 NEP=NEP+NE(NW)
      CALL CALZ (WAVE,NWIRE,A,NE,NN)
      CALL CALZL(NL,NE,NWIRE)
      CALL LINEQ(NEP,LMNJP,MMNJP)
      CALL BIGV(U,NF,NWIRE,NE,NEP)
      CALL CRNT(U,C,NEP)
      WRITE (3,203)
      WRITE (3,208)
      DO 29 I=1,NEP
      CMAG=CABS(C(I))
      CPHASE= ATAN2(AIMAG(C(I)),REAL(C(I)))*180./3.1416
      WRITE (3,51) I,C(I), CMAG,CPHASE
   29 CONTINUE
      YD(1,1)=1.
      YD(2,1)=0.
      YD(3,1)=0.
      YD(1,2)=0.
      YD(2,2)=1.
      YD(3,2)=0.
      YD(1,3)=0.
      YD(2,3)=0.
      YD(3,3)=1.
      WRITE (3,151)
      DO 71 M=1,3
      XM=M
      DO 71 K=1,7,2
      XK=K
      YY(1)=0.
      YY(2)=0.2*XK
      YY(3)=(XM-1.)*0.5
      CALL ENER (WAVE,NWIRE,A,NE,    C,NEP,YY,YD)
      E(2)=2.*PI*YY(2)*E(2)
      E(3)=PI*1.3333333*E(3)
      WRITE (3,202)
      WRITE (3,10) YY(1), YY(2), YY(3)
      WRITE (3,201)
      WRITE (3,207)
      DO 27 J=1,3
      EMAG = CABS ( E(J))
      IF (EMAG.LT.0.1E-9)  GO TO 16
      EPHASE = ATAN2(AIMAG(E(J)),REAL(E(J)))*180./3.1416
      GO TO 17
```

```
      16 EPHASE=0.
      17 CONTINUE
         WRITE (3,51) J,E(J), EMAG,EPHASE
      27 CONTINUE
         WRITE (3,152)
      71 CONTINUE
         GO TO 100
       1 FORMAT ( F10.5,4I5)
       2 FORMAT (3F10.5)
       3 FORMAT(16I5)
       4 FORMAT( 8F10.3)
       5 FORMAT(' BA=',F10.5,'  NS=',I5,'  NF=',I5,'  NL=',I5)
       6 FORMAT(' IF(I)=',16I5)
       7 FORMAT(' V(I)=',8F12.3)
       8 FORMAT(' LP(I)=', 16I5)
       9 FORMAT(' ZL(I)=',8F10.3)
      10 FORMAT ('      X=',E10.3,'  Y=',E10.3,'  Z=', E10.3)
      11 FORMAT('    WAVE =',F20.5)
      12 FORMAT(' NWIRE = ',I5)
      13 FORMAT(' DATA FOR THE ',I5,'TH  WIRE')
      14 FORMAT (2E10.5)
      51 FORMAT (I5,3E12.4,F10.3)

     151 FORMAT(' ********************************************')
     152 FORMAT(' ----------------------------------------')
     201 FORMAT('     FIELD')
     202 FORMAT ('    COORDINATES OF TESTING POINT ')
     203 FORMAT ('  CURRENT DISTRIBUTION')
     207 FORMAT ('     J              E(J)              MAGNITUDE     PHASE')
     208 FORMAT ('     I              C(I)              MAGNITUDE     PHASE')
     300 FORMAT(' ',12E10.2)
     310 FORMAT('  THE COORDINATE OF THE WIRE')
     500 STOP
         END
**WARNING**  FORMAT STATEMENT     14 IS UNREFFRENCED

        $DATA
  WAVE =               4.14879
NWIRE =       1
********************************************
DATA FOR THE      1TH  WIRE
BA=   0.00325  NS=    28   NF=     1   NL=     1
IF(I)=      7
V(I)=          2.000          0.000
LP(I)=      1
ZL(I)=      0.000      0.000

  ----------------------------------------
   THE COORDINATE OF THE WIRE
    0.00E 00  0.00E 00 -0.10E 01  0.00E 00  0.00E 00 -0.93E 00
    0.00E 00  0.00E 00 -0.86E 00  0.00E 00  0.00E 00 -0.79E 00
    0.00E 00  0.00E 00 -0.71E 00  0.00E 00  0.00E 00 -0.64E 00
    0.00E 00  0.00E 00 -0.57E 00  0.00E 00  0.00E 00 -0.50E 00
    0.00E 00  0.00E 00 -0.43E 00  0.00E 00  0.00E 00 -0.36E 00
```

0.00E 00	0.00E 00	-0.29E 00	0.00E 00	0.00E 00	-0.21E 00
0.00E 00	0.00E 00	-0.14E 00	0.00E 00	0.00E 00	-0.71E-01
0.00E 00	0.00E 00	0.00E 00	0.00E 00	0.00E 00	0.71E-01
0.00E 00	0.00E 00	0.14E 00	0.00E 00	0.00E 00	0.21E 00
0.00E 00	0.00E 00	0.29E 00	0.00E 00	0.00E 00	0.36E 00
0.00E 00	0.00E 00	0.43E 00	0.00E 00	0.00E 00	0.50E 00
0.00E 00	0.00E 00	0.57E 00	0.00E 00	0.00E 00	0.64E 00
0.00E 00	0.00E 00	0.71E 00	0.00E 00	0.00E 00	0.79E 00
0.00E 00	0.00E 00	0.86E 00	0.00E 00	0.00E 00	0.93E 00
0.00E 00	0.00E 00	0.10E 01			

****

CURRENT DISTRIBUTION

I	C(I)		MAGNITUDE	PHASE
1	0.7150E-02	-0.2666E-02	0.7631E-02	-20.448
2	0.1227E-01	-0.4340E-02	0.1302E-01	-19.471
3	0.1670E-01	-0.5563E-02	0.1760E-01	-18.422
4	0.2029E-01	-0.6286E-02	0.2124E-01	-17.216
5	0.2294E-01	-0.6471E-02	0.2383E-01	-15.754
6	0.2457E-01	-0.6101E-02	0.2531E-01	-13.947
7	0.2512E-01	-0.4439E-02	0.2551E-01	-10.023
8	0.2457E-01	-0.6101E-02	0.2531E-01	-13.947
9	0.2294E-01	-0.6471E-02	0.2383E-01	-15.754
10	0.2029E-01	-0.6286E-02	0.2124E-01	-17.216
11	0.1670E-01	-0.5563E-02	0.1760E-01	-18.422
12	0.1227E-01	-0.4340E-02	0.1302E-01	-19.471
13	0.7150E-02	-0.2666E-02	0.7631E-02	-20.448

****

COORDINATES OF TESTING POINT

X= 0.000E 00 Y= 0.200E 00 Z= 0.000E 00

FIELD

J	E(J)		MAGNITUDE	PHASE
1	0.0000E 00	0.0000E 00	0.0000E 00	0.000
2	-0.1337E-04	-0.6916E-04	0.7044E-04	-100.944
3	-0.9584E 01	0.1600E 01	0.9717E 01	170.522

COORDINATES OF TESTING POINT

X= 0.000E 00 Y= 0.600E 00 Z= 0.000E 00

FIELD

J	E(J)		MAGNITUDE	PHASE
1	0.0000E 00	0.0000E 00	0.0000E 00	0.000
2	-0.8707E-05	-0.2803E-04	0.2935E-04	-107.256
3	-0.5035E 01	0.2723E 01	0.5724E 01	151.594

```
COORDINATES OF TESTING POINT
 X= 0.000E 00   Y= 0.100E 01   Z= 0.000E 00
FIELD
J              E(J)                MAGNITUDE     PHASE
1  0.0000E 00   0.0000E 00   0.0000E 00      0.000
2 -0.1685E-04 -0.2551E-04   0.3058E-04   -123.446
3 -0.2924E 01   0.3553E 01   0.4601E 01    129.452
----------------------------------------------------
COORDINATES OF TESTING POINT
 X= 0.000E 00   Y= 0.140E 01   Z= 0.000E 00
FIELD
J              E(J)                MAGNITUDE     PHASE
1  0.0000E 00   0.0000E 00   0.0000E 00      0.000
2 -0.2035E-04 -0.5178E-05   0.2100E-04   -165.725
3 -0.8500E 00   0.3685E 01   0.3782E 01    102.988
----------------------------------------------------
COORDINATES OF TESTING POINT
 X= 0.000E 00   Y= 0.200E 00   Z= 0.500E 00
FIELD
J              E(J)                MAGNITUDE     PHASE
1  0.0000E 00   0.0000E 00   0.0000E 00      0.000
2 -0.1269E 01 -0.6008E 01   0.6141E 01   -101.925
3 -0.4910E 01 -0.1231E 00   0.4912E 01   -178.564
----------------------------------------------------
COORDINATES OF TESTING POINT
 X= 0.000E 00   Y= 0.600E 00   Z= 0.500E 00
FIELD
J              E(J)                MAGNITUDE     PHASE
1  0.0000E 00   0.0000E 00   0.0000E 00      0.000
2 -0.1405E 01 -0.4528E 01   0.4741E 01   -107.243
3 -0.4671E 01   0.1612E 01   0.4941E 01    160.962
----------------------------------------------------
COORDINATES OF TESTING POINT
 X= 0.000E 00   Y= 0.100E 01   Z= 0.500E 00
FIELD
J              E(J)                MAGNITUDE     PHASE
1  0.0000E 00   0.0000E 00   0.0000E 00      0.000
2 -0.1675E 01 -0.3163E 01   0.3579E 01   -117.906
3 -0.2781E 01   0.2997E 01   0.4088E 01    132.858
----------------------------------------------------
COORDINATES OF TESTING POINT
 X= 0.000E 00   Y= 0.140E 01   Z= 0.500E 00
FIELD
J              E(J)                MAGNITUDE     PHASE
1  0.0000E 00   0.0000E 00   0.0000E 00      0.000
2 -0.1972E 01 -0.2043E 01   0.2839E 01   -133.991
3 -0.7754E 00   0.3342E 01   0.3430E 01    103.062
----------------------------------------------------
COORDINATES OF TESTING POINT
 X= 0.000E 00   Y= 0.200E 00   Z= 0.100E 01
FIELD
J              E(J)                MAGNITUDE     PHASE
1  0.0000E 00   0.0000E 00   0.0000E 00      0.000
2 -0.1994E 01 -0.5543E 01   0.5891E 01   -109.789
3 -0.9241E 01 -0.1320E 02   0.1612E 02   -124.990
```

COORDINATES OF TESTING POINT
X= 0.000E 00   Y= 0.600E 00   Z= 0.100E 01
FIELD

J	E(J)		MAGNITUDE	PHASE
1	0.0000E 00	0.0000E 00	0.0000E 00	0.000
2	-0.1987E 01	-0.4594E 01	0.5006E 01	-113.392
3	-0.4485E 01	-0.6136E 00	0.4527E 01	-172.209

COORDINATES OF TESTING POINT
X= 0.000E 00   Y= 0.100E 01   Z= 0.100E 01
FIELD

J	E(J)		MAGNITUDE	PHASE
1	0.0000E 00	0.0000E 00	0.0000E 00	0.000
2	-0.2574E 01	-0.3699E 01	0.4506E 01	-124.837
3	-0.2392E 01	0.1946E 01	0.3083E 01	140.874

COORDINATES OF TESTING POINT
X= 0.000E 00   Y= 0.140E 01   Z= 0.100E 01
FIELD

J	E(J)		MAGNITUDE	PHASE
1	0.0000E 00	0.0000E 00	0.0000E 00	0.000
2	-0.3205E 01	-0.2507E 01	0.4069E 01	-141.966
3	-0.5492E 00	0.2530E 01	0.2538E 01	102.017

The material that follows corresponds to the circular loop problem of example two. The subroutines are not listed since they are the same as before. The main program is the same as that used for example one except that the problem geometry is different as specified using statements 402-413, and also the field points of interest are different as specified using statements 454-474.

```
    C       MAIN PROGRAM         MMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMM
370         COMPLEX ZL(4,32),V( 4,32),Z (60,60),U( 60),C(60),
           1E(3), ZIN,CONJG,CI,YIN,CAI,C3I,CC
371         DIMENSION BA(12),A(12),NS(12),  NF(12), NL(12), NCLOSE(12),
           1X(3,4,32),NE(12),NP(12),NN(12),IF(4,32),LP(4,32),XX(3,4,32),
           2XD(3,4,32),TLEN(4,32),LMNOP(60),MMNOP(60),
           3YY(3),YD(3,3)
372         COMMON /COA/XX,XD,TLEN /COB/Z /COC/ZL,LP /COD/V,IF /COE/E
373         PI =3.14159265
374         XMU = 4.0E-7*PI
375         EPSLN = 8.854E-12
376         CI = (0.,1.)
377     100 READ (1,2,  END=500)   WAVE
378         WRITE (3,11) WAVE
379         OMEG=2.997925E8/WAVE*2.*PI
380         BETA = 2.*PI/WAVE
381         READ (1,3) NWIRE
382         WRITE (3,12) NWIRE
383         WRITE (3,151)
384         DO 550 NW=1,NWIRE
385         WRITE (3,13) NW
386         READ (1,1) BA(NW),NS(NW),NF(NW),NL(NW)
387         WRITE (3,5) BA(NW),NS(NW),NF(NW),NL(NW)
388         NFNW=NF(NW)
389         READ(1,3) (IF(NW,I),I=1,NFNW  )
390         WRITE(3,6) (IF(NW,I),I=1,NFNW  )
391         READ    (1,4) (V(NW,I),I=1,NFNW   )
392         WRITE(3,7)    (V(NW,I),I=1,NFNW   )
393         NLNW =NL(NW)
394         READ (1,3)  (LP(NW,I),I=1,NLNW   )
395         WRITE (3,8) (LP(NW,I),I=1,NLNW   )
396         READ (1,4) (ZL(NW,I),I=1,NLNW)
397         WRITE(3,9)  (ZL(NW,I),I=1,NLNW   )
398         WRITE (3,152)
399         NE(NW) = NS(NW)/2-1
400         NP(NW) =NS(NW) +1
401         NN(NW) = 2*NF(NW)+2
402         RID=WAVE/(2.*PI)
403         DPHI=2.*PI/(NS(NW)-2)
404         NPNW=NP(NW)-3
```

```
      DO 1510 I=1,NPNW
      X(1,NW,I)=RID*COS((I-1)*DPHI)
      X(2,NW,I)=RID*SIN((I-1)*DPHI)
 1510 X(3,NW,I)=0
      DO 1511 J=1,3
      NPNW=NP(NW)
      X(J,NW,NPNW)=X(J,NW,3)
      X(J,NW,NPNW-1)=X(J,NW,2)
 1511 X(J,NW,NPNW-2)=X(J,NW,1)
      WRITE (3,310)
      WRITE(3,300) ((X(J,NW,I),J=1,3),I=1,NPNW)
      WRITE (3,152)
  550 CONTINUE
      DO 560 NW=1,NWIRE
      NNNW=NN(NW)
      DO 15 I=1,NNNW
      DO 15 J=1,3
      XX(J,NW,I) = (X(J,NW,I)+X(J,NW,I+1))/2.
   15 XD(J,NW,I)=X(J,NW,I+1)-X(J,NW,I)
      DO 20 I=1,NNNW
   20 TLEN(NW,I) = SQRT(XD(1,NW,I)**2+XD(2,NW,I)**2+XD(3,NW,I)**2)
      A(NW) = BA(NW)*WAVL
  560 CONTINUE
      WRITE(3,151)
      NEP=0
      DO 28 NW=1,NWIRE
   28 NEP=NEP+NE(NW)
      CALL CALZ (WAVE,NWIRE,A,NE,IN)
      CALL CALZL(NE,NE,NWIRE)
      CALL LINE,(NEP,LNNP,MNJP)
      CALL FIGV(U,NF,NWIRE,NE,NEP)
      CALL CPNT(U,C,NEP)
      WRITE (3,203)
      WRITE (3,208)
      DO 29 I=1,NEP
      CMAG=CABS(C(I))
      CPHASE= ATAN2(AIMAG(C(I)),REAL(C(I)))*180./3.1416
      WRITE (3,51) I,C(I), CMAG,CPHASE
   29 CONTINUE
      YD(1,1)=1.
      YD(2,1)=0.
      YD(3,1)=0.
      YD(1,2)=0.
      YD(2,2)=1.
      YD(3,2)=0.
      YD(1,3)=0.
      YD(2,3)=0.
      YD(3,3)=1.
      WRITE (3,151)
      DO 71 K=1,6
      EK=2.**(K-1)-1.
      YY(1)=.02*EK
      YY(2)=0.
      YY(3)=0.
      CALL EULAR (WAVE,NWIRE,A,NE,    C,NEP,YY,YD)
```

```
      WRITE (3,202)
      WRITE (3,10) YY(1), YY(2), YY(3)
      WRITE (3,201)
      WRITE (3,207)
      DO 27 J=1,3
      EMAG = CABS ( E(J))
      IF (EMAG.LT.0.1E-9)  GO TO 16
      EPHASE = ATAN2(AIMAG(E(J)),REAL(E(J)))*180./3.1416
      GO TO 17
   16 EPHASE=0.
   17 CONTINUE
      WRITE (3,51) J,E(J), EMAG,EPHASE
   27 CONTINUE
      WRITE (3,152)
   71 CONTINUE
      GO TO 10
    1 FORMAT ( F10.5,4I5)
    2 FORMAT (8F10.5)
    3 FORMAT(16I5)
    4 FORMAT( 8F10.3)
    5 FORMAT(' BA=',F10.5,'  NS=',I5,'  NF=',I5,'  NL=',I5)
    6 FORMAT(' IF(I)=',16I5)
    7 FORMAT(' V(I)=',8F12.3)
    8 FORMAT(' LP(I)=', 16I5)
    9 FORMAT(' ZL(I)=',8F10.3)
   10 FORMAT ('      X=',E10.3,'  Y=',E10.3,'  Z=', F10.3)
   11 FORMAT('    WAVE =',F20.5)
   12 FORMAT('  NWIRE = ',I5)
   13 FORMAT(' DATA FOR THE ',I5,'TH  WIRE')
   14 FORMAT (2E10.5)
   51 FORMAT (I5,3E12.4,F10.3)
  151 FORMAT(' ***********************************************')
  152 FORMAT(' -----------------------------------------------')
  201 FORMAT('     FIELD')
  202 FORMAT ('     COORDINATES OF TESTING POINT ')
  203 FORMAT ('  CURRENT DISTRIBUTION')
  207 FORMAT ('    J            E(J)            MAGNITUDE     PHASE')
  208 FORMAT ('    I            C(I)            MAGNITUDE     PHASE')
  300 FORMAT(' ',12E10.2)
  310 FORMAT('  THE COORDINATE OF THE WIRE')
  500 STOP
      END
**WARNING**  FORMAT STATEMENT     14 IS UNREFERENCED
```

```
        $DATA
  WAVE =                 0.50000
NWIRE =       1
******************************************
DATA FOR THE      1TH  WIRE
BA=    0.00106  NS=    30  NF=     1  NL=     1
IF(I)=    14
V(I)=        1.000        0.000
LP(I)=       1
ZL(I)=      0.000       0.000
```

```
--------------------------------------------------------
THE COORDINATE OF THE WIRE
 0.80E-01  0.00E 00  0.00E 00  0.78E-01  0.18E-01  0.00E 00  0.72E-01
 0.35E-01  0.00E 00  0.62E-01  0.50E-01  0.00E 00
 0.50E-01  0.62E-01  0.00E 00  0.35E-01  0.72E-01  0.00E 00  0.18E-01
 0.78E-01  0.00E 00  0.10E-06  0.80E-01  0.00E 00
-0.18E-01  0.78E-01  0.00E 00 -0.35E-01  0.72E-01  0.00E 00 -0.50E-01
 0.62E-01  0.00E 00 -0.62E-01  0.50E-01  0.00E 00
-0.72E-01  0.35E-01  0.00E 00 -0.78E-01  0.18E-01  0.00E 00 -0.80E-01
 0.13E-06  0.00E 00 -0.78E-01 -0.18E-01  0.00E 00
-0.72E-01 -0.35E-01  0.00E 00 -0.62E-01 -0.50E-01  0.00E 00 -0.50E-01
-0.62E-01  0.00E 00 -0.35E-01 -0.72E-01  0.00E 00
-0.18E-01 -0.78E-01  0.00E 00 -0.15E-05 -0.80E-01  0.00E 00  0.18E-01
-0.78E-01  0.00E 00  0.35E-01 -0.72E-01  0.00E 00
 0.50E-01 -0.62E-01  0.00E 00  0.62E-01 -0.50E-01  0.00E 00  0.72E-01
-0.35E-01  0.00E 00  0.78E-01 -0.18E-01  0.00E 00
 0.80E-01  0.00E 00  0.00E 00  0.78E-01  0.18E-01  0.00E 00  0.72E-01
--------------------------------------------------------
 0.35E-01  0.00E 00
```

```
*****************************************************
 CURRENT DISTRIBUTION
   I            C(I)                    MAGNITUDE     PHASE
   1   0.4221E-02   0.3083E-02   0.5227E-02     36.145
   2   0.2930E-02   0.1616E-02   0.3346E-02     28.886
   3   0.1066E-02  -0.1118E-04   0.1066E-02     -0.601
   4  -0.9994E-03  -0.1581E-02   0.1871E-02   -122.295
   5  -0.2853E-02  -0.2931E-02   0.4158E-02   -134.774
   6  -0.4143E-02  -0.3736E-02   0.5579E-02   -137.957
   7  -0.4601E-02  -0.4334E-02   0.6120E-02   -136.757
   8  -0.4143E-02  -0.3736E-02   0.5579E-02   -137.955
   9  -0.2858E-02  -0.2931E-02   0.4158E-02   -134.769
  10  -0.9990E-03  -0.1581E-02   0.1870E-02   -122.283
  11   0.1067E-02  -0.1130E-04   0.1057E-02     -0.607
  12   0.2930E-02   0.1616E-02   0.3346E-02     28.882
  13   0.4221E-02   0.3083E-02   0.5227E-02     36.144
  14   0.4682E-02   0.4346E-02   0.6388E-02     42.874
*****************************************************
   COORDINATES OF TESTING POINT
    X= 0.000E 00   Y= 0.000E 00   Z= 0.000E 00
   FIELD
   J            E(J)                    MAGNITUDE     PHASE
   1  -0.7919E-04   0.2463E-03   0.2587E-03    107.824
   2  -0.6722E 01   0.2178E 01   0.7066E 01    162.042
   3   0.0000E 00   0.0000E 00   0.0000E 00      0.000
```

```
------------------------------------------
COORDINATES OF TESTING POINT
 X= 0.200E-01   Y= 0.000E 00   Z= 0.000E 00
FIELD
J            E(J)                 MAGNITUDE      PHASE
1 -0.7657E-04   0.2656E-03   0.2765E-03   106.078
2 -0.7234E 01   0.2099E 01   0.7532E 01   163.829
3  0.0000E 00   0.0000E 00   0.0000E 00     0.000



------------------------------------------
COORDINATES OF TESTING POINT
 X= 0.600E-01   Y= 0.000E 00   Z= 0.000E 00
FIELD
J            E(J)                 MAGNITUDE      PHASE
1  0.3620E-04   0.5723E-03   0.5734E-03    86.381
2 -0.1105E 02   0.1515E 01   0.1115E 02   172.190
3  0.0000E 00   0.0000E 00   0.0000E 00     0.000
------------------------------------------
COORDINATES OF TESTING POINT
 X= 0.140E 00   Y= 0.000E 00   Z= 0.000E 00
FIELD
J            E(J)                 MAGNITUDE      PHASE
1 -0.1320E-03 -0.1289E-03   0.1845E-03  -135.676
2 -0.2897E 01 -0.1876E 00   0.2903E 01  -176.295
3  0.0000E 00   0.0000E 00   0.0000E 00     0.000
------------------------------------------
COORDINATES OF TESTING POINT
 X= 0.300E 00   Y= 0.000E 00   Z= 0.000E 00
FIELD
J            E(J)                 MAGNITUDE      PHASE
1 -0.1414E-04   0.2550E-04   0.2916E-04   119.000
2  0.1374E 00   0.1272E 01   0.1279E 01    83.834
3  0.0000E 00   0.0000E 00   0.0000E 00     0.000
------------------------------------------
COORDINATES OF TESTING POINT
 X= 0.620E 00   Y= 0.000E 00   Z= 0.000E 00
FIELD
J            E(J)                 MAGNITUDE      PHASE
1 -0.1362E-05 -0.5976E-05   0.6130E-05  -102.842
2 -0.4901E 00 -0.3786E 00   0.6193E 00  -142.318
3  0.0000E 00   0.0000E 00   0.0000E 00     0.000
------------------------------------------
```