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RADC-TR-76-101, Volume VI (of seven) Phase Report February 1978

APPLICATIONS OF MULTICONDUCTOR TRANSMISSION LINE THEORY TO THE PREDICTION OF CABLE COUPLING, A Digital Computer Program for Determining Terminal Currents Induced in a Multiconductor Transmission Line by an Incident Electromagnetic Field

Clayton R. Paul

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University of Kentucky



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ROME AIR DEVELOPMENT CENTER Air Force Systems Command Griffiss Air Force Base, New York 13441



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PREFACE

This effort was conducted by The University of Kentucky under the sponsorship of the Rome Air Development Center Post-Doctoral Program for RADC's Compatibility Branch. Mr. Jim Brodock of RADC was the task project engineer and provided overall technical directiona and guidance.

The RADC Post-Doctoral Program is a cooperative venture between RADC and some sixty-five universities eligible to participate in the program. Syracuse University (Department of Electrical Engineering), Purdue University (School of Electrical Engineering), Georgia Institute of Technology (School of Electrical Engineering), and State University of New York at Buffalo (Department of Electrical Engineering) act as prime contractor schools with other schools participating via sub-contracts with the prime schools. The U.S. Air Force Academy (Department of Electrical Engineering), Air Force Institute of Technology (Department of Electrical Engineering), and the Naval Post Graduate School (Department of Electrical Engineering, also participate in the program.

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Defense Command (ADC), Hq USAF, Defense Communications Agency (DCA), Navy, Army, Aerospace Medical Division (AMD), and Federal Aviation Administration (FAA).

Further information about the RADC Post-Doctoral Program can be obtained from Mr. Jacob Scherer, RADC/RBC, Griffiss AFB, NY, 1344J, telephone Autovon 587-2543, commercial (315)330-2543.

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The author wishes to acknowledge the capable efforts of Ms. Donna To n in typing this manuscript.

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I. INTRODUCTION

The problem of determining the currents induced in termination networks at the ends of a multiconductor transmission line by an incident electromagnetic field is obviously quite important in determining the electromagnetic compatibility of electronic systems. The digital computer program described in this report is intended to be used for this purpose.

The special case of a transmission line consisting of two wires (cylindrical conductors) immersed in a general, nonuniform field was considered by Taylor, Satterwhite and Harrison [3]. The equations for the terminal currents obtained in [3] were placed in a more convenient form by Smith [4]. The special case of a uniform plane wave incident on a three-wire line (the three wires lie in a plane) in the transverse direction (perpendicular to the transmission line longitudinal (x) axis) with the electric field intensity vector polarized parallel to the line axis was obtained by Harrison in [5]. Paul has extended these special case results to (n+1) conductor (multiconductor) lines for an arbitrary incident electromagnetic field [1,6].

This report describes a digital computer program, WIRE, which is designed to calculate the sinusoidal,steady state,terminal currents induced at the ends of a uniform, multiconductor transmission line which is illuminated by an incident electromagnetic field. Three types of transmission line structures are considered. TYPE 1 structures consist of (n+1) parallel wires. TYPE 2 structures consist of n wires above an infinite ground plane. 1YPE 3 structures consist of n wires within an overall, cylindrical shield.

For each structure type, one of the conductors is designated as the reference conductor for the line voltages. For TYPE 1 structures, the

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reference conductor is one of the (n+1) wires. For TYPE 2 structures, the reference conductor is the ground plane. For TYPE 3 structures, the reference conductor is the overall, cylindrical shield.

All of the transmission lines are considered to be uniform in the sense that there is no variation in the cross-sections of the (n+1) conductors along the transmission line axis and all (n+1) conductors are parallel to each other. All conductors are considered to be perfect conductors and the surrounding medium is considered to be homogeneous, linear, isotropic and lossless.

The incident field can be in the form of a uniform plane wave for TYPE 1 and TYPE 2 structures or a nonuniform field for all structure types. The uniform plane wave excitation is specified by data entries describing the magnitude of the electric field intensity vector, the orientation of this vector and the direction of propagation. These quantities will be made precise in the following chapters. For the nonuniform field, the data entries are the values of the incident electric field intensity (magnitude and phase) at points along the axes of the conductors and along contours between the wires at the two ends of the line. Piecewise-linear behavior of the fields (magnitude and phase) is assumed between these data points.

The primary restrictions on the program are that the cross-sectional dimensions of the line, e.g., conductor separations, are much smaller than a wavelength at the frequency in question and the ratios of conductor separation to wire radii are greater than approximately 5. The first restriction is imposed to insure (in a qualitative fashion) that only the TEM mode of propagation is significant, i.e., the higher order modes are nonpropagating. This requirement that the cross-sectional dimensions of the

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line are electrically small must also be imposed to insure that the definition of voltage is independent of path if the incident field is not curl free in the line's cross-sectional plane. (See Chapter II.) The second restriction is necessary to insure the validity of the entries in the per-unit-length transmission line inductance and capacitance matrices. The entries in these matrices are derived by assuming that the per-unit-length charge distributions on the wires are essentially constant around the peripheries of the wires, i.e., the wires are separated from each other sufficiently to insure that proximity effect is not a factor.

General termination structures are provided for at the ends of the transmission line. These terminations are assumed to be linear.

Chapter II contains the derivation of the equations for general field excitations. Chapter III contains a derivation of the equivalent sources induced in the structure types by uniform plane waves as well as nonuniform fields. Chapter IV contains a discussion of the contents of the program. Chapter V contains a User's Manual and Chapter VI contains examples which are used to check the program operation.

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II. MODEL DERIVATIONS

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Cross-sections of the three basic types of structures considered by the program are shown in Figure 2-1. The axis of the line is the x coordinate and the (n+1) conductors are perpendicular to the y,z plane as indicated in Figure 2-1. The TYFE 1 structure consists of (n+1) wires in which one of the wires is designated as the reference conductor for the line voltages. The TYPE 2 structure consists of n wires above an infinite ground plane where the ground plane is the reference conductor for the line voltages. The TYPE 3 structure consists of n wires within an overall cylindrical shield. In this case, the shield is the reference conductor.

All conductors are considered to be perfect conductors and the surrounding medium is considered to be homogeneous, linear, isotropic and lossless. The surrounding medium (homogeneous) is characterized by a permittivity ε and a permeability μ . Throughout this report, the permeability and permittivity of free space will be denoted by $\mu_v = 4\pi \times 10^{-7}$ and $\varepsilon_v \cong (1/36\pi) \times 10^{-9}$, respectively, and the permeability and permittivity of the medium are related to the free space values by the relative permeability, μ_r , and relative permittivity (relative dielectric constant), ε_r , as $\mu = \mu_r \mu_v$ and $\varepsilon = \varepsilon_r \varepsilon_v$, respectively. For structure TYPE 1 and TYPE 2, a logical choice for ε_r and μ_r would be 1 (free space). For structure TYPE 3, a logical choice for the relative permeability, μ_r , would be 1 as is typical of dielectrics. The program, however, allows for any ε_r and μ_r for all structure types.

The n wires are labeled from 1 to n and the radius of the i-th wire is denoted by r_{wi} . The reference conductor is designated as the zero-th conductor. For TYPE 1 structures, the reference wire has radius r_{w0} and the

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center-to-center separation between the i-th and j-th wires is designated as d_{ij} . For TYPE 2 structures, the i-th wire is at a height h_i about the ground plane with a center-to-center separation between the i-th and j-th wires of d_{ij} . For TYPE 3 structures, the interior radius of the cylindrical shield is designated by r_s , the i-th wire is at a distance r_i from the shield center and the angular separation between the i-th and j-th wires is designated by θ_{ij} .

Implicit in the following is the requirement for the transmission line to be uniform. Transmission lines considered here are uniform in the sense that all (n+1) conductors have uniform cross-sections along the line axis and all n wires are parallel to each other and the reference conductor.

2.1 Derivation of the Multiconductor Transmission Line Equations

The distributed parameter transmission line equations for multiconductor lines with incident field illumination can be derived and are similar (with matrix notation employed) to the familiar equations for two-conductor lines [1,2,6,7,8]. Assuming sinusoidal excitation at a radian frequency $\omega = 2\pi f$, the electric field intensity vector, $\vec{e}(x,y,z,t)$, and the magnetic field intensity vector, $\vec{\mu}(x,y,z,t)$, are written as $\vec{e}(x,y,z,t) = \vec{E}(x,y,z)e^{j\omega t}$ and $\vec{\mu}(x,y,z,t) = \vec{H}(x,y,z)e^{j\omega t}$. The complex vectors $\vec{E}(x,y,z)$ and $\vec{H}(x,y,z)$ are the phasor quantities. Line voltages, $\mathcal{V}_i(x,t) = V_i(x)e^{j\omega t}$, of the i-th conductor with respect to the zeroth conductor (the reference conductor) are defined as the line integral of \vec{e} between the two conductors along a path in the y,z plane. $V_i(x)$ is the complex phasor voltage. The line current, $J_i(x,t) = I_i(x)e^{j\omega t}$ associated with the i-th conductor and directed in the x direction is defined as the line integral of \vec{H} along a closed contour in the y,z plane encircling only the i-th conductor and $I_i(x)$ is the complex phasor current.

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The current in the reference conductor, $\oint_0 (x,t) = I_0 e^{j\omega t}$, satisfies $I_0 = \sum_{i=1}^n (-I_i(x))$.

It is convenient to consider the effects of the spectral components of the incident field as per-unit-length distributed sources along the line. The sources appear as series voltage sources and shunt current sources as indicated in Figure 2-2 for an "electrically small" Δx section of the line. The multiconductor transmission line equations may then be derived for the Δx subsection in Figure 2-2 in the limit as $\Delta x \rightarrow 0$ as a set of 2n coupled, complex, ordinary differential equations [1],

$$V(x) + j\omega LI(x) = V_{x}(x)$$
 (2-1a)

$$I(x) + j\omega CV(x) = I_s(x)$$
(2-1b)

A matrix M with m rows and n columns is denoted as mxn and the element in the i-th row and j-th column is denoted by $[M]_{ij}$. $\underline{V}(x)$ and $\underline{I}(x)$ are nxl vectors of the line voltages and currents, respectively. The elements in the i-th rows are $[\underline{V}(x)]_i = V_i(x)$ and $[\underline{I}(x)]_i = I_i(x)$ and $[\dot{V}(x)]_i =$ $(d/dx)V_i(x)$. The nxn real, symmetric, constant matrices L and C are the per-unit-length inductance and capacitance matrices, respectively. From Figure 2-2 one can derive (2-1) and the entries in L and C become [1]

$$\begin{bmatrix} L \\ - \end{bmatrix}_{ii} = \ell_i + \ell_0 - 2m_{i0}$$
(2-2a)

$$\begin{bmatrix} L \\ ij \end{bmatrix} = l_0 + m_{ij} - m_{i0} - m_{j0}$$
 (2-2b)
i≠j

and

$$\begin{bmatrix} C \\ \vdots \end{bmatrix}_{ii} = c_{i0} + \sum_{\substack{j=1 \\ i \neq j}}^{n} c_{ij}$$
(2-3a)

$$\begin{bmatrix} c \\ j \\ i \neq j \end{bmatrix} = -c_{ij}$$
(2-3b)



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Figure 2-2. The per-unit-length model.

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The entries in $\underline{V}_{s}(x)$ and $\underline{I}_{s}(x)$ are the per-unit-length distributed sources along the line induced by the incident field, i.e., $[\underline{V}_{s}(x)] = V_{si}(x)$ and $[\underline{I}_{s}(x)] = I_{si}(x)$, as shown in Figure 2-2.

In order to consider general termination networks (and allowing independent sources in these networks) we may characterize these as generalized Thevenin equivalents [1]. For a line of total length \mathcal{I} , the equations for the termination networks at x = 0 and x = \mathcal{I} are

$$\underline{V}(0) = \underline{V}_{0} - \underline{Z}_{0} \underline{I}(0)$$
(2-4a)
$$\underline{V}(\mathbf{I}) = \underline{V}_{\mathbf{I}} + \underline{Z}_{\mathbf{I}} \underline{I}(\mathbf{I})$$
(2-4b)

where \underline{V}_0 and $\underline{V}_{\underline{\chi}}$ are nxl vectors of equivalent open circuit port excitation voltages, $[\underline{V}_0]_{\underline{i}} = V_{0\underline{i}}$ and $[\underline{V}_{\underline{\chi}}]_{\underline{i}} = \underline{V}_{\underline{\chi}\underline{i}}$, and \underline{Z}_0 and $\underline{Z}_{\underline{\chi}}$ are nxn symmetric impedance matrices as shown in Figure 2-3. This is, of course, a completely general and arbitrary characterization of these linear termination networks. The entries in these cermination equations can be easily determined for a given network by considering $V_{\underline{i}}(0)$ and $V_{\underline{i}}(\underline{z})$ (the termination port voltages) as independent sources, and writing the loop current equations for each network where $I_{\underline{i}}(0)$ and $I_{\underline{i}}(\underline{z})$ are subsets of the loop currents in each network. (See Section 2.6.)

With the line immersed in a homogeneous medium with permittivity ϵ and permeability μ , the product of L and C becomes [1]

$$LC = CL = \mu \epsilon 1 \qquad (2-5)$$

where l_n is the nxn identity matrix with ones on the main diagonal and zeros elsewhere, i.e., $[\tilde{l}_n]_{ii} = 1$, and $[l_n]_{ij} = 0$, $i \neq j$. For this case, the solution to (2-1) and (2-4) is in a simple form [1]



Figure 2-3. The termination networks.

$$[\cos(kz)\{Z_{0} + Z_{z}\} + j \sin(kz) \{Z_{0} + Z_{z}Z_{0}^{-1}Z_{0}\}] \underline{I}(0)$$

= $-\underline{v}_{z}$ + $[j \sin(kz) Z_{z}Z_{0}^{-1} + \cos(kz)]_{n}] \underline{v}_{0}$
+ $\hat{\underline{v}}_{s}(z) - Z_{z}\hat{\underline{I}}_{s}(z)$ (2-6a)

$$\underline{I}(x) = -j \sin(\kappa x) Z_{C}^{-1} Y_{0}$$

+ $[\cos(kx)]_{n}^{1} + j \sin(kx) Z_{C}^{-1} Z_{0}] \underline{I}(0) + \hat{\underline{I}}_{s}(x)$ (2-6b)

where the wavenumber is $k = 2\pi/\lambda$, $\lambda = v/f$, $v = 1/\sqrt{\mu\epsilon} = v_0/\sqrt{\mu}r_r$, $v_0 = 1/\sqrt{\mu}v_v$ and the nxn characteristic impedance matrix, Z_C , is [1]

$$Z_{C} = v L \qquad (2-7)$$

The inverse of an nxn matrix M is denoted by M^{-1} and $\hat{V}_{s}(z)$ and $\hat{I}_{s}(z)$ in (2-6) are given by [1]

$$\hat{\underline{V}}_{s}(z) = \int_{0}^{z} \{\cos(k(z'-x)) \ \underline{V}_{s}(x) \}$$

$$-j \sin(k(z'-x)) \ \underline{Z}_{c} \underline{I}_{s}(x) \} dx$$

$$\hat{\underline{I}}_{s}(z) = \int_{0}^{z} \{\cos(k(z'-x)) \ \underline{I}_{s}(x) \} dx$$

$$-j \sin(k(z'-x)) \ \underline{Z}_{c} \underbrace{-1}_{s}^{z}(x) \} dx.$$
(2-8b)

Solution of (2-6a) for the current vector, $\underline{I}(0)$, requires the solution of n complex equations in n unknowns ($I_{\underline{i}}(0)$). Once (2-6a) is solved, (2-6b) yields the currents $\underline{I}(\boldsymbol{z})$ directly.

In this report, no independent excitation sources in the termination networks will be considered. The program XTALK described in Vol. VII of this series [2] can be used to compute the contribution to the response due to these sources. Thus the source vectors in the generalized Thevenin equivalent representations in (2-4) will be zero, i.e., $V_0 = V_{-1} = 0$ where the matrix, 0, has zeros in every position, i.e., [0] = 0 for m^p_1 i = 1, ..., m and j=1, ..., p. Thus the generalized Thevenin equivalent representation becomes

$$V(0) = -Z_0 I(0)$$
 (2-9a)

$$V(\mathbf{I}) = Z_{\mathbf{I}} \mathbf{I}(\mathbf{I})$$
 (2-9b)

and the equations for the terminal currents in (2-6) become

$$[\cos(k\mathbf{x}) \{ \sum_{n=0}^{Z} + \sum_{n=1}^{Z} \} + j \sin(k\mathbf{x}) \{ \sum_{n=0}^{Z} + \sum_{n=1}^{Z} \sum_{n=0}^{-1} \sum_{n=1}^{Z} \}] \underline{I}(0) =$$

$$(2-10a)$$

$$\underbrace{\hat{V}}_{\mathbf{s}}(\mathbf{x}) - \sum_{\mathbf{x}} \widehat{\mathbf{I}}_{\mathbf{s}}(\mathbf{x})$$

$$\underline{I}(\mathbf{x}) = [\cos(k\mathbf{x})]_{n} + j \sin(k\mathbf{x}) \sum_{n=1}^{-1} \sum_{n=1}^{Z}] \underline{I}(0) + \widehat{\mathbf{I}}_{\mathbf{s}}(\mathbf{x})$$

$$(2-10b)$$

As an alternative formulation, a generalized Norton equivalent representation may be used to characterize the termination networks. It we define $Y_0 = Z_0^{-1}$ and $Y_{\chi} = Z_0^{-1}$ the generalized Norton equivalent representation becomes

$$I'(0) = -Y_0 V(0)$$
 (2-11a)

$$I(\tau) = Y_{\tau} V(\tau)$$
 (2-11b)

Equations (2-10) can then be written as

$$[\cos(kz) \{ Y_0 + Y_z \} + j \sin(kz) \{ Y_1 \neq Z_c = Y_0 + Z_c^{-1} \}] \underline{V}(0) =$$

$$\hat{I}_s(z) - Y_z \hat{V}_s(z)$$

$$I(z) = -[\cos(kz) + Y_0 + j \sin(kz) + Z_c^{-1}] \underline{V}(0) + \hat{I}_s(z) (2-12b)$$

where I(0) can be recovered from V(0) via (2-11a).

There remain two basic problems: determining the entries in the perunit-length inductance and capacitance matrices, L and C, and determining the equivalent source vectors, $\hat{\underline{V}}_{s}(z)$ and $\hat{\underline{I}}_{s}(z)$, which are induced by the incident electromagnetic field. The derivations of L and C for the three structure types have been given previously [1,9] and will be summarized in the following sections. It will become clear in the following section that once the equivalent source vectors, $\hat{\underline{V}}_{s}(z)$ and $\hat{\underline{I}}_{s}(z)$, are determined for the TYPE 1 structure, they can be immediately obtained for the TYPE 2 and TYPE 3 structures with a parallel development. Thus the basic problem is the determination of these equivalent source vectors for the TYPE 1 structure.

2.2 Derivation of the Equivalent Induced Source Vectors, $\hat{Y}_{s}(\boldsymbol{x})$ and $\hat{I}_{s}(\boldsymbol{x})$, for TYPE 1 Structures

In order to determine the equivalent induced sources, $V_{si}(x)$ and $I_{si}(x)$, consider Figure 2-4. The method used in [3] can be adapted here in a similar fashion. Faraday's law in integral form becomes

$$\oint_{C_i} \vec{E} \cdot dC_i = -j\omega\mu \int_{S_i} \vec{H} \cdot \vec{n} dS_i$$
(2-13)

where S_i is a flat, rectangular surface in the x,y plane between wire i and wire 0 and between x and x + Δx as shown in Figure 2-4. The unit normal \vec{x}_i is $\vec{n} = \vec{z}$ where \vec{z} is the unit vector in the z direction, $dS_i = dx dy$ and C_i is a contour encircling S_i in the proper direction (counter-clockwise according to the right-hand rule). Equation (2-13) becomes for the indicated integration¹

¹In integrating from y=0 to y=d_{i0}, we are implicitly assuming that the wires are sufficiently separated so that they may be replaced by infinitesimally small filaments of current (charge).



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Figure 2-4.

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$$\int_{0}^{d_{i0}} [E_{ti}(y, x + \Delta x) - E_{ti}(x, y)] dy$$

-
$$\int_{x}^{x+\Delta x} [E_{li}(d_{i0}, x) - E_{li}(0, x)] dx$$

=
$$-j\omega\mu \int_{0}^{x+\Delta x} \int_{0}^{d_{i0}} H_{ni}(y, x) dy dx$$
 (2-14)

where E_{ti} is the component of the total electric field (incident plus scattered) transverse to the line axis and lying along a straight line joining the two conductors i.e., $E_{ti} = E_y$; E_{li} is the component of the total electric field along the longitudinal axis of the line, i.e., $E_{li} = E_x$; and H_{ni} is the component of the total magnetic field perpendicular to the plane formed by the two wires, i.e., $H_{ni} = H_z$.

Defining the voltage between the two wires as

$$V_{i}(x) = -\int_{0}^{d_{10}} E_{ti}(y,x) dy$$
 (2-15)

then

$$-\frac{dV_{i}(x)}{dx} = \lim_{\Delta x \to 0} \frac{1}{\Delta x} \int_{0}^{d_{i0}} [E_{ti}(y, x + \Delta x) - E_{ti}(y, x)] dy \qquad (2-16)$$

The total electric field along the wire surfaces is zero since we assume perfect conductors. (One can straightforwardly include finite conductivity conductors through a surface impedance as was done in [3]). Therefore (2-14) becomes in the limit as $\Delta x \neq 0$

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$$\frac{dV_{i}(x)}{dx} = j\omega\mu \int_{0}^{d} i0 H_{ni}(y,x) dy.$$
 (2-17)

The total magnetic field is the sum of an incident and a scattered field

$$H_{ni} (y,x) = H_{z}(y,x)$$

$$= \underbrace{(scat)}_{z} \underbrace{(inc)}_{y,x)+} \underbrace{(j,x)}_{y,z}$$
(2-18)
(2-18)
(2-18)

and the scattered field here is considered to be produced by the transmission line currents. The scattered flux passing between the two conductors per unit of line length is directly related to the scattered magnetic field and the per-unit-length inductance matrix, L, as

$$\begin{aligned} &(\text{scat}) \\ \phi_{i}(x) &= - \int_{0}^{d} i0 \quad (\text{scat}) \\ & \mu H_{ni}(y, x) \, dy \\ &= \left[\ell_{11}, \ell_{12}, \dots, \ell_{1n} \right] \begin{bmatrix} I_{1}(x) \\ I_{2}(x) \\ \vdots \\ \vdots \\ I_{n}(x) \end{bmatrix}$$
(2-19)

where $\ell_{ij} = [L]_{ij}$. Substituting (2-19) and (2-18) into (2-17) and arranging for $i = 1, \dots, n$ yields

$$\underbrace{\underline{V}(\mathbf{x}) + j\omega \underline{L}\underline{I}(\mathbf{x})}_{\sim} = \begin{bmatrix} j\omega\mu \int_{-1}^{0} \frac{d}{10} (inc) \\ H(y,x) dy \\ 0 \\ \vdots \end{bmatrix}$$
(2-20)

-16-

and the source vector $\underline{V}_{s}(\mathbf{x})$ in (2-1) is easily identified by comparing (2-20) and (2-1).

For transmission line theory to apply, the cross-sectional dimensions of the line (wire spacing, etc.) must be electrically small, i.e., $kd_{10} \ll 1$. Thus the result indicates that the voltage, V_{si} , induced in the loop between the ith conductor and the zeroth conductor and between x and $x + \Delta x$ is equal to the rate of change of the incident flux penetrating this "electrically small" loop which, of course, makes sense.

Ampere's law yields

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$$E_{y} = \frac{1}{j\omega\varepsilon} \left[\frac{\partial H_{x}}{\partial z} - \frac{\partial H_{z}}{\partial x} \right]$$
(2-21)

 ${\ensuremath{\mathtt{E}}}_y$ will consist of scattered and incident field components and is written as

$$E_{ti}(y,x) = E_{y}(y,x)$$

$$(scat) = (inc)$$

$$= E_{y}(y,x) + E_{y}(y,x).$$

$$(2-22)$$

$$(z-22)$$

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$$(z-22)$$

$$(z-22)$$

$$(z-22)$$

Substituting (2-21) into (2-15) we have

$$V_{i}(x) = -\int_{0}^{d_{i0}} E_{y}(y,x) dy$$

= $\frac{1}{j\omega\varepsilon} \int_{0}^{d_{i0}} \left\{ \frac{\partial H_{z}(y,x)}{\partial x} + \frac{\partial H_{z}(y,x)}{\partial x} - \frac{\partial H_{x}(y,x)}{\partial z} - \frac{\partial H_{x}(y,x)}{\partial z} \right\} dy.$ (2-23)

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Utilizing (2-19) we obtain

$$V_{i}(x) = -\frac{1}{j\omega\mu\epsilon} \frac{d}{dx} \{ [\ell_{i1}, \ell_{i2}, \dots, \ell_{in}] \ \underline{I}(x) \}$$

$$-\frac{1}{j\omega\epsilon} \int_{0}^{d} \frac{\partial H_{x}(y, x)}{\partial z} dy - \int_{0}^{d} \frac{\partial I_{0}(inc)}{\partial E_{ti}(y, x)} dy. \quad (2-24)$$

If we assume that the currents on the wires are directed only in the x direction, i.e., there are no transverse components of the currents on (scat) the wire surfaces , then $H_x(y,x) = 0$ and (2-24) becomes

$$V_{i}(x) = -\frac{1}{j\omega\mu\epsilon} \frac{d}{dx} \{ [\ell_{11}, \ell_{12}, \dots, \ell_{1n}] \ \underline{I}(x) \}$$

$$- \int_{0}^{d_{10}} \frac{(inc)}{E_{ti}(y, x)} \ dy.$$
(2-25)

Arranging these equations for i = 1, ..., n we obtain the second transmission line equation

$$\underbrace{\mathbf{i}}_{(\mathbf{x})} + \mathbf{j}_{\omega\mu\epsilon} \mathbf{L}^{-1} \mathbf{V}(\mathbf{x}) = -\mathbf{j}_{\omega\mu\epsilon} \mathbf{L}^{-1} \begin{bmatrix} \mathbf{d}_{\mathbf{i0}} (\mathbf{inc}) \\ \mathbf{d}_{\mathbf{i0}} (\mathbf{inc}) \\ \mathbf{E}_{\mathbf{ti}} (\mathbf{y}, \mathbf{x}) d\mathbf{y} \end{bmatrix}.$$
(2-26)

Utilizing (2-5) in (2-26) ($C = \mu \epsilon L^{-1}$) we obtain by comparing (2-20) and (2-26) to (2-1)

$$\underline{V}_{s}(x) = j\omega\mu \begin{bmatrix} d_{i0} (inc) \\ H_{i}(y,x) dy \\ 0 \\ \vdots \end{bmatrix}$$
(2-27a)

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$$\underline{I}_{s}(x) = -j\omega C \begin{bmatrix} d_{i0} & (inc) \\ E_{ti}(y,x) & dy \\ 0 & \vdots \end{bmatrix}$$
(2-27b)

The shunt current sources in $\underline{I}_{s}(x)$ are therefore a result of the line voltage induced by the incident electric field being applied across the per-unit-length line-to-line capacitances which, of course, satisfies our intuition.

The final problem remaining is to obtain simplified versions of $\hat{\underline{V}}_{s}$ and $\hat{\underline{I}}_{s}$ in (2-8) to be directly used in (2-10) and (2-12). First consider the determination of $\hat{\underline{V}}_{s}(z)$. Substituting (2-27) into (2-8a) yields

$$\frac{\hat{\mathbf{y}}_{\mathbf{s}}(\mathbf{z}) = j\omega\mu \int_{0}^{\mathbf{z}} \left\{ \cos \left(\mathbf{k}(\mathbf{z} - \mathbf{x})\right) \\
\times \left[\int_{0}^{d} \frac{10 (\text{inc})}{H_{\text{ni}}(\mathbf{y}, \mathbf{x})} d\mathbf{y} \right] \right\} d\mathbf{x} \\
- k \int_{0}^{\mathbf{z}} \left\{ \sin \left(\mathbf{k}(\mathbf{z} - \mathbf{x})\right) \\
\times \left[\int_{0}^{d} \frac{10 (\text{inc})}{E_{\text{ti}}(\mathbf{y}, \mathbf{x})} d\mathbf{y} \right] \right\} d\mathbf{x}.$$
(2-28)

From Faraday's law we obtain

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Substituting this into (2-28) yields

$$\begin{split} \hat{\underline{v}}_{s}(\boldsymbol{z}) &= \int_{0}^{\boldsymbol{z}} \left\{ \cos\left(k\left(\boldsymbol{z}-\mathbf{x}\right)\right) \begin{bmatrix} (\operatorname{inc}) & (\operatorname{inc}) \\ F_{li}\left(d_{10},\mathbf{x}\right) & \cdots & F_{li}\left(0,\mathbf{x}\right) \end{bmatrix} \right\} d\mathbf{x} \\ &- \int_{0}^{\boldsymbol{z}} \left\{ \cos\left(k\left(\boldsymbol{z}-\mathbf{x}\right)\right) & (\operatorname{inc}) & \vdots \\ & \left(\operatorname{inc}\right) & \vdots \\ & \left(\int_{0}^{d_{10}} \frac{\partial E_{ti}(\mathbf{y},\mathbf{x})}{\partial \mathbf{x}} & d\mathbf{y} \right] \right\} d\mathbf{x} \\ &- k \int_{0}^{\boldsymbol{z}} \left\{ \sin\left(k\left(\boldsymbol{z}-\mathbf{x}\right)\right) & (2-30) \\ &- k \int_{0}^{\boldsymbol{z}} \left\{ \sin\left(k\left(\boldsymbol{z}-\mathbf{x}\right)\right) & (2-30) \\ & \left(\int_{0}^{d_{10}} \frac{(\operatorname{inc})}{E_{ti}(\mathbf{y},\mathbf{x})} & d\mathbf{y} \right] \right\} d\mathbf{x}. \end{split}$$

Utilizing Leibnitz's rule (see [10, p. 219]), (2-30) is equivalent to

$$\frac{\tilde{\Psi}_{s}(\boldsymbol{\chi}) = \int_{0}^{\boldsymbol{\chi}} \left\{ \cos \left(k(\boldsymbol{\chi} - \boldsymbol{x}) \right) \\
\left\{ \begin{array}{c} \left(\operatorname{inc} \right) & \vdots & \left(\operatorname{inc} \right) \\
E_{\ell i} \left(d_{10}, \boldsymbol{x} \right) & \vdots & E_{\ell i} \left(0, \boldsymbol{x} \right) \\
- \int_{0}^{\boldsymbol{\chi}} \left\{ \frac{\partial}{\partial \boldsymbol{x}} \left\{ \cos \left(k(\boldsymbol{\chi} - \boldsymbol{x}) \right) \right\} \right\} d\boldsymbol{x} \\
\left\{ \begin{array}{c} \left(\int_{0}^{d} i0 & \left(\operatorname{inc} \right) \\
E_{t i} \left(\boldsymbol{y}, \boldsymbol{x} \right) & d\boldsymbol{y} \\
\end{array} \right\} \right\} d\boldsymbol{x}$$
(2-31)

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and this may be written as

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$$\begin{split} \hat{\underline{v}}_{s}(\boldsymbol{z}) &= \int_{0}^{\boldsymbol{z}} \begin{cases} \cos \left(k\left(\boldsymbol{z}-x\right)\right) \\ \left(\begin{array}{c} (\operatorname{inc}) \\ E_{li}(d_{10},x) - E_{li}(0,x) \\ \vdots \\ \end{array} \right) \end{cases} dx \\ &= \left[\int_{0}^{d_{10}} (\operatorname{inc}) \\ E_{ti}(\boldsymbol{x},\boldsymbol{z}) dy \\ \vdots \\ + \cos \left(k\boldsymbol{z}\right) \left[\int_{0}^{d_{10}} (\operatorname{inc}) \\ E_{ti}(y,0) \\ \vdots \\ \end{array} \right] dy. \end{split}$$

Similarly
$$\hat{\underline{l}}_{s}(\boldsymbol{x})$$
 may be obtained as

$$\hat{\underline{l}}_{s}(\boldsymbol{x}) = -iZ_{c}^{-1} \int_{0}^{\boldsymbol{x}} \begin{cases} \sin (k(\boldsymbol{x} - \boldsymbol{x})) \\ \sin (k(\boldsymbol{x} - \boldsymbol{x})) \end{cases}$$

$$\bigvee \begin{bmatrix} (\operatorname{inc}) \\ E_{\ell 1}(d_{10}, \boldsymbol{x}) - E_{\ell 1}(0, \boldsymbol{x}) \\ \vdots \end{bmatrix} d\boldsymbol{x}$$

$$(2-33)$$

$$= iZ_{c}^{-1} \left\{ \sin (k\boldsymbol{x}) \left[\int_{0}^{d_{10}} (\operatorname{inc}) \\ E_{t1}(y, 0) dy \right] \right\}$$

The important quantity in (2-10a) is $\hat{\underline{V}}_{s}(z) - Z_{z}\hat{\underline{I}}_{-s}(z)$. Combining (2-32) and (2-33), this becomes

$$\frac{\hat{\mathbf{v}}_{s}(\mathbf{z}) - Z_{z}\hat{\mathbf{L}}_{-s}(\mathbf{z})}{\sum_{k=0}^{z} \left[\cos \left(k(\mathbf{z} - \mathbf{x}) \right) \frac{1}{2n} + j \sin \left(k(\mathbf{z} - \mathbf{x}) \right) Z_{z}Z_{c}^{-1} \right]}{\sum_{k=0}^{z} \left[\cos \left(k(\mathbf{z} - \mathbf{x}) \right) \frac{1}{2n} + j \sin \left(k(\mathbf{z} - \mathbf{x}) \right) \right]} d\mathbf{x} \\
\times \left[\left[(inc) & (inc) \\ E_{li}(d_{10}, \mathbf{x}) - E_{li}(0, \mathbf{x}) \\ \vdots & (1 - E_{li}(0, \mathbf{x})) \right] \right] d\mathbf{x} \\
- \left[\int_{0}^{d} \frac{10}{E_{ti}(y, \mathbf{z})} \right] d\mathbf{y} \\
\vdots \\
+ \left[\cos \left(k\mathbf{z} \right) \frac{1}{2n} + j \sin \left(k\mathbf{z} \right) Z_{c} Z_{c}^{-1} \right] \\
\vdots \\
\vdots \\$$
(2-34)

 $X\left[\int_{0}^{d_{i0}} \sum_{E_{ti}(y,0)}^{(inc)}\right] dy.$

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The final equations for the line currents then become (substituting (2-34) into (2-10)

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$$[\cos(kz) \{ Z_0 + Z_z Z \} + j \sin(kz) \{ Z_c + Z_z Z_{-c}^{-1} Z_0 \}] I(0) =$$

$$\int_0^z \{ [\cos(k(z'-x))]_{zn}^1 \qquad (2-35a) + j \sin(k(z'-x))]_{zn}^2 \sum_{z=0}^{-1} \{ I_{z}^{(inc)} + I_{z}^{(inc)} + I_{z}^{(inc)} \} dx - E_{t}(z) + \{ [\cos(kz)]_{zn}^1 + j \sin(kz) Z_z Z_{-c}^{-1} \} E_{t}^{(inc)} \}$$

$$\underline{I}(z) = [\cos(kz)]_{n} + j \sin(kz)Z_{0}^{-1}Z_{0}] \underline{I}(0)$$

- $jZ_{0}^{-1} \int_{0}^{z} {\sin(k(z-x))} \frac{(inc)}{E_{\ell}(x)} dx$ (2-35b)
- $jZ_{0}^{-1} {\sin(kz)} \frac{(inc)}{E_{\ell}(0)}$

(inc) (inc) (inc) where $\underline{E}_{\ell}(x)$, $\underline{E}_{t}(x)$, and $\underline{E}_{t}(0)$ are nxl column vectors with the entries in the i-th rows given by

$$\begin{array}{ccc} (inc) & (inc) & (inc) \\ [\underline{E}_{\ell}(x)]_{i} &= E_{\ell i}(d_{i0}, x) - E_{\ell i}(0, x) \end{array} (2-36a)$$

$$\begin{bmatrix} (inc) \\ [\underline{E}_{t}(z)]_{i} \end{bmatrix} = \int_{0}^{d} \begin{bmatrix} i0 & (inc) \\ E_{ti}(\rho_{i},z) & d\rho_{i} \end{bmatrix}$$
(2-36b)

$$\begin{bmatrix} (inc) \\ [\underline{E}_{t}(0)]_{i} \end{bmatrix} = \int_{0}^{d_{i0}} \begin{bmatrix} (inc) \\ E_{ti}(\rho_{i}, 0) & d\rho_{i} \end{bmatrix}$$
(2-36c)

for i = 1, ..., n.

A word of caution in the interpretation of the notation is in order. Although it should be clear from the derivation, the reader should never-(inc) theless be reminded that the integration path for the component E_{ti} is in the y direction when the i-th conductor is concerned. When other conductors are concerned, the integration path is a straight line in the y,z plane which joins the conductor and the zeroth conductor and is perpendicular to these two conductors. This is designated as ρ_i in (2-36) and replaces the y variable for the path associated with conductors i and 0. The notation may be cumbersome but the idea and the implementation are quite simple.

Defining the vectors

$$M = \int_{0}^{\chi} \cos (k(\chi - x)) \frac{E_{\chi}}{E_{\chi}} (x) dx \qquad (2-37a)$$

$$\underline{N} = \int_{0}^{\mathbf{Z}} \sin (k(\mathbf{Z} - \mathbf{x})) \underline{E}_{k}^{(inc)} (\mathbf{x}) d\mathbf{x}$$
(2-37b)

we may write (2-35) as

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$$[\cos (k\mathbf{x}) \{ Z_0 + Z \} + j \sin (k\mathbf{x}) \{ Z_C + Z_z Z_z^{-1} Z_0 \}] \underline{I}(0)$$

$$= \underline{M} + j Z_z Z_c^{-1} \underline{N} - \underline{E}_t(\mathbf{x})$$

$$+ [\cos (k\mathbf{x})]_{n}^1 + j \sin (k\mathbf{x}) Z_z Z_c^{-1}] \underline{E}_t(0)$$

$$(2-38a)$$

$$\underline{I}(z) = [\cos(kz) \ \underline{1}_{n} + j \ \sin(kz) \ \underline{Z}_{C}^{-1} \underline{Z}_{0}] \ \underline{I}(0)$$

$$- j \ \underline{Z}_{C}^{-1} \ \underline{N} - j \ \underline{Z}_{C}^{-1} \ \{\sin(kz) \ \underline{E}_{t}(0)\}$$
(2-38b)
(2-38b)
For the generalized Norton equivalent representation, equations (2-38) can be written as

$$[\cos(kz) \{ Y_{20} + Y \} + j \sin(kz) \{ Y_{2} Z_{0} Y_{1} + Z_{0}^{-1} \}] [-\Psi(0)] =$$

$$Y_{2} M + j Z_{0}^{-1} N - Y_{2} [E_{t}^{(inc)}(z)]$$

$$+ [\cos(kz) Y_{2} + j \sin(kz) Z_{0}^{-1}] [E_{t}^{(inc)}(0)]$$

$$(2-39a)$$

$$\underline{I}(z) = [\cos(kz) Y_0 + j \sin(kz) Z_c^{-1}][-\underline{V}(0)]$$

$$-j Z_c^{-1} N - j Z_c^{-1} {\sin(kz) \underline{E}_t^{(inc)}(0)}$$
(2-39b)

and $\underline{I}(0)$ is obtained from $\underline{I}(0) = -\underline{Y}_0 \underbrace{V}(0) = \underline{Y}_0[-\underline{V}(0)]$.

2.3 Determining the Per-Unit-Length Inductance Matrix, L, for TYPE 1 Structures

For TYPE 1 structures, one final calculation remains; the determination of the per-unit-length inductance matrix, L, which is related to the characteristic impedance, Z_{C} , via (2-7). Ordinarily this is a difficult calculation [11]. However, if we assume that the wires are separated sufficiently such that the charge distribution around the periphery of each wire is constant, then the wires can be replaced by filamentary lines of charge. Typically, this will be accurate if the smallest ratio of wire separation to wire radius is greater than approximately 5 [11]. In this case, the entries in L for TYPE 1 structures are given by [1,9]

$$\begin{bmatrix} L \\ \vdots \end{bmatrix}_{ii} = \mu \epsilon \begin{bmatrix} C \\ \vdots \end{bmatrix}_{ii} = \frac{\mu}{2\pi} \ln(\frac{\frac{d}{10}}{r_{wi}r_{w0}})$$
(2-40a)

-25-

$$\begin{bmatrix} L \\ ij \\ i \neq j \end{bmatrix}_{\substack{i=1 \\ i \neq j}} = \mu \epsilon \begin{bmatrix} C \\ ij \end{bmatrix}_{ij} = \frac{\mu}{2\pi} \ln \left(\frac{d_{i0}d_{j0}}{r_{w0}d_{ij}}\right)$$
(2-40b)

For closer wire spacings, proximity effect will alter the charge distribution from constant ones and numerical approximations must be employed to find C and L [11]. Although the entries in L have been derived elsewhere, we shall show a direct derivation which relates the scattered flux passing between the wires to the wire currents as was used in (2-19).

The matrix L relates the scattered flux $(\overset{\text{scat})}{\Phi}$ passing between the wires to the wire currents as

$$(\operatorname{scat})_{\underline{\phi}} = \begin{bmatrix} \varphi_{1} & \cdots & \varphi_{1} \\ \vdots \\ \vdots \\ (\operatorname{scat}) \\ \varphi_{n} \end{bmatrix} = \begin{bmatrix} \varphi_{11} & \cdots & \varphi_{1n} \\ \vdots & \cdots & \vdots \\ \vdots \\ \varphi_{n1} & \cdots & \varphi_{nn} \end{bmatrix} \begin{bmatrix} I_{1} \\ \vdots \\ I_{n} \end{bmatrix}$$
(2-41)

The respective entries are determined as

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$$k_{ii} = \frac{\phi_{i}}{I_{i}} | I_{1}, \cdots, I_{i-1}, I_{i+1}, \cdots, I_{n} = 0$$
(2-42a)

(scat)

$$\begin{pmatrix} & & & \\ & & & \\ ij & & & \\ & i \neq j & & \\ & i \neq j & & \\ & & & & \\$$

and $\ell_{ij} = \ell_{ji}$. Large wire separations are assumed so that the wires may be replaced by filaments of current. When the wires are not widely separated, accurate values for L can be obtained by numerical methods [11].

Consider Figure 2-5(a). The magnitude of the magnetic field intensity

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(a)

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(b)

Figure 2-5.

vector due to I $_{\rm i}$ on wire i at a distance r>r $_{\rm wi}$ away from wire i is

$$H_{r} = \frac{I_{i}}{2\pi r}$$
(2-43)

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and the total flux passing between wire i and wire 0 due to both currents is

Thus ℓ_{ii} is easily identified as in (2-40a).

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(scat) Consider Figure 2-5(b). The portion of the flux ϕ_i passing between wire i and wire 0 due to -I_j in the reference conductor is as above

$$\substack{\text{(scat)} \\ \phi_{10} = \frac{\mu I_{j}}{2\pi} \quad \ln \left(\frac{d_{10}}{r_{\mu 0}}\right) }$$
(2-45)

and the portion of the flux passing between wire i and wire 0 due to I in the jth conductor can be found to be

$$\begin{aligned} \text{(scat)} &= -\mu \int_{0}^{d} \frac{10}{\mu_{n}} H_{n} d\rho & (2-46) \\ &= -\frac{\mu}{2\pi} I_{j} \{ \int_{\rho=0}^{\rho=d} \frac{10}{[\xi_{0}^{2} + (\rho - \rho_{0})^{2}]} d\rho \} \\ &= \frac{\mu}{2\pi} I_{j} \{ \frac{1}{2} \ln \left[-\frac{(\xi_{0}^{2} + \rho_{0}^{2})}{\xi_{0}^{2} + (d_{10} - \rho_{0})^{2}} \right] \} \end{aligned}$$

-28-

Combining (2-45) and (2-46) we obtain

(scat) (scat) (scat)
$$\mu I_{j} = \frac{\mu I_{j}}{2\pi} \ln \left(\frac{d_{j0}d_{10}}{d_{1j}r_{w0}} \right)$$
 (2-47)

since

$$d_{ij}^{2} = \xi_{0}^{2} + (d_{i0} - \rho_{0})^{2}$$
 (2-48a)

$$d_{j0}^{2} = \xi_{0}^{2} + \rho_{0}^{2}$$
(2-48b)

and l_{11} is easily identified as in (2-40b).

2.4 <u>Determination of the Equivalent Induced Source Vectors and the Per-</u> Unit-Length Inductance Matrix for TYPE 2 Structures

Consider the system of n wires above an infinite ground plane shown in Figure 2-1(b). The result for (n+1) wires given in (2-35) - (2-39) can be extended to this case with the following observations. Consider Figure 2-6. Clearly we may apply Faraday's law in the previous development to the flat, rectangular surface in the x,y plane shown in Figure 2-6(b) between the ground plane and the i-th wire and between x and x+ Δx . This flat, rectangular surface S₁ lies in the x,y plane. Equations (2-35) -(2-39) will again be obtained. Equations (2-36) become for this case

(inc) (inc) (inc)
$$[\underline{E}_{l}(x)]_{i} = \underline{E}_{li}(h_{i},x) - \underline{E}_{li}(0,x)$$
 (2-49a)

$$\begin{bmatrix} (inc) \\ [\underline{E}_{t}(\mathbf{X})]_{i} = \int_{0}^{h_{i}} \underbrace{(inc)}_{E_{ti}(\rho_{i},\mathbf{X}) d\rho_{i}} (2-49b)$$

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$$\begin{bmatrix} (inc) \\ E_{t}(0) \end{bmatrix}_{i} = \int_{0}^{h_{i}} E_{ti}(\rho_{j}, 0) d\rho_{i}$$
(2-49c)

where ρ_i is a straight-line contour in the y,z plane between the position of the ground plane, y=0, and the i-th wire, and is perpendicular to the ground plane, i.e. $\rho_i = y$. This is indicated in Figure 2-6(a).

(inc) $E_{li}(h_{i},x)$ is the component of the incident electric field parallel (inc) to the axis of the i-th wire at y=h_i and $E_{li}(0,x)$ is the component of the incident field parallel to the ground plane directly beneath the i-th wire. In the program, it assumed that the net incident electric field (the vector sum of the incident field in the absence of the ground plane and the portion of this field which is reflected by the ground plane) is obtained. Therefore $F_{li}(0,x) = 0$. $E_{ti}^{(inc)}$ is the component of the incident electric field parallel to ρ_{i} and directed in the +y direction.

The per-unit-length inductance matrix, L, can be obtained in a fashion similar to Section 2.3 by determining the scattered magnetic flux passing through the surface S_i between the i-th wire and the position of the ground plane (the ground plane is replaced by image wires) and is given by [1,9]

$$[L]_{ii} = \frac{\mu}{2\pi} \ln \left(\frac{2h_i}{r_{wi}}\right)$$
(2-50a)

$$\begin{bmatrix} L \\ \vdots \end{bmatrix}_{ij} = \frac{\mu}{2\pi} \ln \left(\frac{d_{ij}^{*}}{d_{ij}} \right)$$
(2-50b)
 $i \neq j$

for i, j=1, ---, n where

$$d_{ij} * = d_{ij}^{2} + 4h_{i}h_{j}$$
 (2-51)

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2.5 Determination of the Equivalent Induced Source Vectors and the Per-Unit-Length Inductance Matrix for TYPE 3 Structures

Consider the system of n wires within an overall, cylindrical shield shown in Figure 2-1(c). Obviously, a parallel development to that of Section 2-2 and 2-4 can be used to obtain the equations (2-35) - (2-39). The image of the i-th wire (assuming the i-th wire can be replaced by a filament) is located at a distance of r_{s/r_i}^2 from the shield center as shown in Figure 2-7 [1]. Equations (2-36) become for this case

$$\begin{bmatrix} (inc) \\ [\frac{r}{t} (\chi) \end{bmatrix}_{i} = \int_{0}^{r_{s}-r_{i}} \begin{bmatrix} (inc) \\ E_{ti}(\rho_{i}, \chi) \end{bmatrix} d\rho i$$
 (2-52b)

$$\begin{bmatrix} (inc) \\ [E_t(0)]_i \end{bmatrix} = \int_{0}^{r_s - r_i} E_{ti}(\rho_i, 0) d\rho_i$$
(2-52c)

where ρ_i is a straight-line contour in the y,z plane between the i-th wire and its image and beginning at the interior of the shield. This contour is on a line between the i-th wire and its image.

 $E_{\chi i}(r_s - r_i, x)$ is the component of the incident electric field parallel (inc) to the axis of the i-th wire at $y=r_s-r_i$ and $E_{\chi i}(0,x)$ is the component of the incident field parallel to the axis of the shield on the interior of the surface. In the program, it is assumed that the net incident electric (inc) (inc) field is obtained so that $E_{\chi i}(0,x) = 0$. E_t is the component of the incident electric field parallel to ρ_i and directed in the +y direction.

The per-unit-length inductance matrix, L, can be obtained in a fashion

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Figure 2-7.

similar to Section 2.3 by determining the scattered magnetic flux passing through a surface between the i-th wire and interior of the shield in the y,x plane and is given by [1,9]

$$\begin{bmatrix} L \\ \vdots \end{bmatrix}_{ii} = \frac{\mu}{2\pi} ln \left(\frac{r_s^2 - r_i^2}{r_s r_{wi}} \right)$$
(2-53a)

$$\begin{bmatrix} L \\ ij \\ = \frac{\mu}{2\pi} \ln \left\{ \left(\frac{r_{j}}{r_{s}} \right) / \frac{\left(r_{i}r_{j} \right)^{2} + r_{s}^{4} - 2r_{i}r_{j}r_{s}^{2} \cos \theta_{ij}}{\left(r_{i}r_{j} \right)^{2} + r_{j}^{4} - 2r_{i}r_{j}^{3} \cos \theta_{ij}} \right\}$$

$$i \neq j \qquad (2-53b)$$

where 0_{ij} is the angular separation between the i-th and j-th wires (see Figure 2-1).

2.6 <u>Determining the Entries in the Termination Network Impedance</u> (Admittance) Matrices

In order to implement this method, one is required to determine the entries in the $n_{\lambda}n$ terminal impedance (admittance) matrices, Z_0 and Z_{χ} (Y_0 and Y_{χ}), which characterize the termination networks at the two ends of the line as:

$$\underbrace{\underline{V}(0) = -\underline{Z}_{0} \underline{I}(0)}_{\underline{V}(\mathbf{I}) = \underline{Z}_{\mathbf{X}} \underline{I}(\mathbf{I})}$$
The venin Equivalent (2-54a)

$$\underbrace{I(0) = -Y_0 \quad V(0)}_{I(t) = Y_t \quad V(t)}$$
 Norton Equivalent (2-54b)

In these matrix equations, the entries in the i-th rows of the nxl vectors

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 $\underline{V}(0)$ and $\underline{V}(\mathbf{x})$ are the line voltages of the i-th wire (with respect to the reference conductor) at x=0 and x= \mathbf{X} , respectively. The entries in the i-th rows of the nxl vectors $\underline{I}(0)$ and $\underline{I}(\mathbf{x})$ are the line currents in the i-th wire (directed in the +x direction) at x=0 and x= \mathbf{X} , respectively.

The most straightforward situation occurs when each wire is directly connected to the reference conductor via a single impedance as shown in Figure 2-8. In this case we may write

$$V_{i}(0) = -Z_{0i} I_{i}(0)$$
 (2-55a)

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$$V_{i}(x) = Z_{i} I_{i}(x)$$
 (2-55b)

for i=1,---,n

and may easily identify the entries in Z_0 and $Z_{\star} \star^{as}$

$$z_{0} = \begin{bmatrix} z_{01} & 0 = - - - - 0 \\ 0 & z_{02} \\ 0 & - - - - - 0 \\ 0 & z_{01} \\ 0 & - - - - - 0 \\ 0 & z_{0n} \end{bmatrix}$$
(2-56a)



-35-



Figure 2-8.

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Clearly, the entries in Y_0 and Y_{\pm} for this case become

$$\mathbf{Y}_{0} = \begin{bmatrix} (1/Z_{01}) & 0 & - & - & 0 \\ 0 & (1/Z_{02}) & 0 \\ 1 & 0 & 0 \\ 0 & - & - & - & 0 \end{bmatrix}$$
(2-57a)

)

$$Y_{z} = \begin{bmatrix} (1/Z_{z1}) & 0 = - - - 0 \\ 0 & (1/Z_{z2}) \\ 1 & 0 \\ 0 = - - - - 0 \\ 1 \\ 0 = - - - - 0 \\ (1/Z_{zn}) \end{bmatrix}$$
(2-57b)

Note that $Y_0 = Z_0^{-1}$ and $Y_{\chi} = Z_{\chi}^{-1}$. In this case, determining the entries in the terminal impedance (admittance) matrices is a trivial matter and the terminal impedance (admittance) matrices are diagonal.

The more difficult case occurs when each wire is not connected directly to the reference conductor by a single impedance. Two examples which illustrate this situation are shown in Figure 2-9. First consider the situation in Figure 2-9(a). Here it is obviously not possible to obtain terminal impedance (admittance) matrices which are diagonal. The termination impedance matrices can, however, be obtained by defining loop currents in which two of the loop currents so defined are the terminal currents $I_1(0)$ and $I_2(0)$. Writing the required three loop equations we obtain

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j.

$$V_{2}(0) = -Z_{1} I_{b} - Z_{3}(I_{b} - I_{c}) - Z_{4}(I_{b} + I_{a} - I_{c})$$

$$V_{1}(0) = -Z_{2} I_{a} - Z_{4}(I_{a} + I_{b} - I_{c})$$

$$0 = Z_{5} I_{c} + Z_{3}(I_{c} - I_{b}) + Z_{4}(I_{c} - I_{a} - I_{b})$$

The objective is to eliminate the current I_c from these equations leaving $I_a = I_1(0)$ and $I_b = I_2(0)$ as a function of $V_1(0)$ and $V_2(0)$. The third equation yields

$$I_{c} = \frac{(Z_{3} + Z_{4}) I_{b} + Z_{4} I_{a}}{(Z_{3} + Z_{4} + Z_{5})}$$

Substituting this result for I into the first two equations eliminates the current I from these equations and leaves

 $V_1(0) = Z_a I_1(0) + Z_b I_2(0)$ $V_2(0) = Z_c I_1(0) + Z_d I_2(0)$

where Z_a , Z_b , Z_c , Z_d are the resulting combinations of Z_1 , Z_2 , Z_3 , Z_4 , Z_5 and we have substituted $I_1(0) = I_a$, $I_2(0) = I_b$.

This technique can obviously be generalized for any number of wires and additional extraneous loops in the termination networks. Treating the n line voltages as independent sources and writing the required number of loop equations for the terminal network, we may obtain

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In (2-58) we may eliminate the extraneous loop currents $\hat{I}_1 - \hat{I}_m$ by solving the second set of equations to yield

$$\hat{I}_{1} \\ \vdots \\ \hat{I}_{m} \\ \hat{I}_{m} \\ \hat{I}_{m} \\ \hat{I}_{m} \\ \hat{I}_{n} \\ \hat{I}$$

Substituting this result into the first set of equations we obtain

$$\begin{bmatrix} V_{1}(0) \\ \vdots \\ V_{n}(0) \end{bmatrix} = (A - B D^{-1} C) \begin{bmatrix} I_{1}(0) \\ \vdots \\ \vdots \\ I_{n}(0) \end{bmatrix}$$
(2-60)

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Clearly, then we may identify

$$Z_{0} = - (A - B D^{-1} C)$$
 (2-61)

The extension of this technique to obtain the Norton Equivalent characterization employs a dual technique. Here we define node voltages (with respect to the reference conductor at either x=0 or x=Z) of all nodes of the termination network (including the n nodes connected to the line) and write the node voltage equations of the network treating the line currents as independent sources. Therefore we write (for x=Z)

$$\begin{bmatrix} I_{1}(\boldsymbol{x}) \\ \vdots \\ \vdots \\ I_{n}(\boldsymbol{x}) \\ 0 \\ \vdots \\ 0 \end{bmatrix} = \begin{bmatrix} I \\ i \\ i \\ i \\ n\chi n \\ i \\ n\chi n \\ m\chi n \\ m\chi n \end{bmatrix} \begin{bmatrix} v_{1}(\boldsymbol{x}) \\ \vdots \\ v_{n}(\boldsymbol{x}) \\ v_{1} \\ \vdots \\ v_{n}(\boldsymbol{x}) \\ v_{n} \end{bmatrix}$$
(2-62)

Eliminating the extraneous node voltages $\hat{v}_1, \dots, \hat{v}_m$ we obtain $\begin{bmatrix} \hat{v}_1 \\ \vdots \\ \hat{v}_m \end{bmatrix} = - \hat{D}^{-1} \hat{C} \begin{bmatrix} v_1(z) \\ \vdots \\ v_n(z) \end{bmatrix}$ (2-63)

Substituting we obtain

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$$\begin{bmatrix} \mathbf{I}_{1}(\mathbf{z}) \\ \vdots \\ \vdots \\ \mathbf{I}_{n}(\mathbf{z}) \end{bmatrix} = \begin{pmatrix} \hat{\mathbf{A}} - \hat{\mathbf{B}} \hat{\mathbf{D}}^{-1} \hat{\mathbf{C}} \end{pmatrix} \begin{bmatrix} \mathbf{V}_{1}(\mathbf{z}) \\ \vdots \\ \mathbf{V}_{n}(\mathbf{z}) \end{bmatrix}$$
(2-64)

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and the terminal admittance matrix is identified as

$$Y_{x} = (\hat{A} - \hat{B} \hat{D}^{-1} \hat{C})$$
 (2-65)

As an example of a Norton Equivalent formulation, consider the termination network in Figure 2-9(b). Here we may write

$$I_{3}(z) = (1/Z_{1}) V_{3}(z)$$

$$I_{2}(z) = (1/Z_{2}) [V_{2}(z) - V_{1}(z)]$$

$$I_{1}(z) = (1/Z_{2}) [V_{1}(z) - V_{2}(z)]$$

Thus we may identify $Y_{\frac{1}{2}}$ by writing

$$\begin{bmatrix} I_{1}(z) \\ I_{2}(z) \\ I_{3}(z) \end{bmatrix} = \begin{bmatrix} 1/z_{2} & -1/z_{2} & 0 \\ -1/z_{2} & 1/z_{2} & 0 \\ 0 & 0 & 1/z_{1} \end{bmatrix} \begin{bmatrix} V_{1}(z) \\ V_{2}(z) \\ V_{3}(z) \end{bmatrix}$$

Note for this example, it is not possible to obtain the Thevenin Equivalent characterization, Z_{x} , since Y_{x} is an obviously singular matrix.

III. <u>DERIVATION OF THE EXCITATION SOURCES FOR UNIFORM PLANE</u> WAVE AND NONUNIFORM FIELD EXCITATIONS

In the previous Chapter, equations for the terminal currents of the line were derived for general forms of the excitation field. In this Chapter, we will derive explicit formulas for the equivalent induced source vectors for uniform plane wave excitation of TYPE 1 and TYPE 2 structures. The coordinate system and reference directions for the incident field which are assumed by the program will be indicated. The formulas for nonuniform field excitation which assume a spatial piecewise linear characterization of the incident field will also be derived.

In the following, some confusion may arise concerning the use of the word "vector". A spatial or physical vector will be denoted as \vec{E} . A matrix or column array vector is denoted by \underline{E} . These two "vectors" are obviously quite different quantities however the word "vector" will be used for both with the distinction between the two, although generally obvious from the context, being denoted by an arrow, \rightarrow , over the symbol or a bar, -, under the symbol.

The equations for the terminal currents of the line for all structure types are repeated here for convenient reference. If the Thevenin equivalent characterization of the terminal networks is chosen:

$$V(0) = -Z_0 I(0)$$
 (3-1a)

$$\underline{V}(\underline{x}) = Z_{\underline{x}} \underline{I}(\underline{x})$$
(3-1b)

then the equations for the terminal currents are

$$\begin{bmatrix} \cos(k\mathbf{x}) \{ Z_0 + Z_1 \} + j \sin(k\mathbf{x}) \{ Z_1 + Z_2 Z_1^{-1} Z_0 \}] I(0) \\ (inc) \\ = M + j Z_1 Z_2^{-1} N - E_1(\mathbf{x}) + [\cos(k\mathbf{x}) I_1 + j \sin(k\mathbf{x}) Z_2 Z_2^{-1}] E_1(0) \\ I(\mathbf{x}) = -j Z_2^{-1} \{ N + \sin(k\mathbf{x}) E_1(0) \} \\ + [\cos(k\mathbf{x}) I_1 + j \sin(k\mathbf{x}) Z_2^{-1} Z_0] I(0) \end{bmatrix}$$
(3-2a)
(3-2a) (3-2a

If the Norton equivalent characterization of the terminal networks is chosen:

$$I(0) = -Y_0 V(0)$$
 (3-3a)

$$\underline{I}(\boldsymbol{z}) = \underbrace{Y}_{\boldsymbol{z}} \underbrace{V}(\boldsymbol{z}) \tag{3-3b}$$

then the equations for the terminal currents are

$$[\cos(kz) \{Y_0 + Y\} + j \sin(kz) \{Y_{z} Z_{c} Y_{inc} + Z_{c}^{-1}\}] [-V(0)]$$

$$= Y_{z} M + j Z_{c}^{-1} N - Y_{z} E_{t}(z)$$

$$+ [\cos(kz) Y_{z} + j \sin(kz) Z_{c}^{-1}] E_{t}(0)$$

$$(3-4a)$$

$$\underline{I}(\mathbf{x}) = -j \sum_{C}^{-1} \{ \underline{N} + \sin(k\mathbf{x}) = \underbrace{E_{t}}_{C}(0) \}$$

+ [cos (k\mathbf{x}) Y_{0} + j sin(k\mathbf{x}) Z_{C}^{-1}] [-V(0)] (3-4b)

(inc) (inc) The nxl induced source vectors \underline{M} , \underline{N} , $\underline{E}_t(0)$, $\underline{E}_t(\mathbf{x})$, in these equations are defined in the previous Chapter for the various structure types and the entries in these vectors are due to the incident field. It is the purpose of this Chapter to derive the entries in these vectors for uniform plane wave illumination of TYPE1 and TYPE2 structures and nonuniform field illumination of all structure types.

3.1 Basic Integrals

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(inc) (inc) The entries in the induced source vectors, \underline{M} , \underline{N} , $\underline{E}_{t}(0)$, $\underline{E}_{t}(\mathbf{x})$, in (3-2) and (3-4) all involve integrals of components of the incident electric field

intensity vector along certain spatial contours. It is, of course, highly desirable for computer implementation to obtain closed form solutions for these integrals. Throughout the following derivations, we will encounter two fundamental integrals which must be evaluated. These are designated as El(a,b,k) and E2(a,b,k) and are given by

$$E1(a,b,k) = \int_{a}^{b} x e^{jkx} dx$$
 (3-5a)

$$E2(a,b,k) = \int_{a}^{b} e^{jkx} dx$$
 (3-5b)

The straightforward solutions of these integrals are

El(a,b,k) =
$$(\frac{be^{jkb} - ae^{jka}}{jk}) + (\frac{e^{jkb} - e^{jka}}{k^2})$$
 (3-6a)

$$E2(a,b,k) = \left(\frac{e^{jkb} - e^{jka}}{jk}\right)$$
 (3-6b)

Note that when k=0, evaluation of the solutions in (3-6) will result in obvious problems. Of course, the integrals in (3-5) have well defined solutions for k=0 and these are quite obviously

E1(a,b,0) =
$$\frac{b^2 - a^2}{2}$$
 (3-7a)

$$E2(a,b,0) = b-a$$
 (3-7b)

For values of the argument k equal to zero, the program evaluates (3-7).

The following solutions for the entries in the induced source vectors (inc) (inc) <u>M</u>, <u>N</u>, <u>E</u>_t(0), <u>E</u>_t(z) in (3-2) and (3-4) will be written in terms of these integrals and the fundamental integrals are stored in the program as function

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subprograms. (See Section 4.2.)

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3.2 Derivation of the Source Vectors for Uniform Plane Wave Illumination and TYPE 1 Structures

(inc) (inc) The basic source vector quantities, M, N, $\underline{E}_t(0)$, $\underline{E}_t(f)$, involved in the equations for the terminal currents in (3-2) and (3-4) for TYPE 1 structures are given in (2-36) and (2-37) which are

$$\begin{array}{ccc} (inc) & (inc) & (inc) \\ [\underline{E}_{\ell}(x)]_{i} &= E_{\ell i} & (d_{i0}, x) - E_{\ell i} & (0, x) \end{array}$$
 (3-8a)

$$\begin{bmatrix} (inc) \\ [\underline{E}_{t}(\mathbf{x})]_{i} = \int_{0}^{d} \begin{bmatrix} i0 & (inc) \\ E_{ti}(\rho_{i},\mathbf{x}) & d \rho_{i} \end{bmatrix}$$
(3-8b)

$$\begin{bmatrix} (inc) \\ [E_{t}(0)]_{i} \end{bmatrix} = \int_{0}^{d_{i0}} \begin{bmatrix} (inc) \\ E_{ti}(\rho_{i}, 0) & d \rho_{i} \end{bmatrix}$$
(3-8c)

$$\underline{M} = \int_{0}^{\mathcal{L}} \underbrace{(inc)}_{\cos(k(\mathcal{L} - x))} \underbrace{\underline{E}}_{\ell}(x) dx \qquad (3-8d)$$

$$\underline{N} = \int_{0}^{\mathbf{L}} \sin(k(\mathbf{L} - \mathbf{x})) \underbrace{\underline{E}}_{\ell}(\mathbf{x}) d\mathbf{x}$$
(3-8e)

(inc) (inc) where $E_{li}(d_{10},x)$ and $E_{li}(0,x)$ are the components of the incident electric field in the x direction (along the line axis) along the i-th wire and along (inc) (inc) the reference wire, respectively. The quantities $E_{ti}(\rho_i, \mathbf{I})$ and $E_{ti}(\rho_i, 0)$ are the components of the incident electric field along a straight-line contour joining the i-th wire and the reference wire in planes (y,z) transverse or perpendicular to the line axis at x= \mathbf{I} and x=0, respectively. This contour is denoted by ρ_i .

The coordinate system used to define the wire positions and shown in Figure 2-4 is used to define the angle of arrival of the uniform plane wave

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and polarization of the incident electric field intensity vector. In defining the wire positions for TYPE 1 structures, an arbitrary rectangular coordinate system is established with the reference wire at the center (y=0, z=0) of this coordinate system as shown in Figure 3-1. The i-th wire has coordinates $y=y_i$, $z=z_i$, relative to this coordinate system. The direction of propagation of the incident wave is defined in Figure 3-2 by the angles Θ_p and ϕ_p . The angle Θ_g is the angular orientation of the electric field intensity vector, \vec{E} , in the plane containing \vec{E} (which is perpendicular to the direction of propagation) and measured from the projection of the y axis onto this plane. The zero phase reference is taken at the origin of the coordinate system, i.e., x=0, y=0, z=0.

The electric field intensity vector can be written in terms of components as [12]

$$\vec{E}^{(i\underline{n}c)}[E_{xm} \vec{x} + E_{ym} \vec{y} + E_{zm} \vec{z}] e^{-j(k_x x + k_y y + k_z z)}$$
(3-9)

The items E_{xm} , E_{ym} , E_{zm} are the magnitudes of the projections of $\vec{E}^{(inc)}$ in the x,y and z directions, respectively and $\vec{x}, \vec{y}, \vec{z}$ are unit vectors in the x,y, and z directions, respectively. The quantities k_x , k_y , and k_z are the components of the propagation constant, k, in the x,y and z directions, respectively. To determine these quantities, note that the electric field intensity vector can be most directly related to a spherical coordinate system in terms of the unit vectors $\vec{r}, \vec{0}, \vec{\phi}$ as shown in Figure 3-2. In this spherical coordinate system, we may write [12]

$$\vec{E} = (E_{rm} \vec{r} + E_{\Theta m} \vec{\Theta} + E_{\phi m} \vec{\phi}) e$$
 (3-10)

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Figure 3-1. The TYPE 1 structure.



Note: Zero Phase Reference Taken at x=0, y=0, z=0.

Figure 3-2. Definition of the uniform plane wave parameters.

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where from Figure 3-2

$$E_{rm} = 0$$
 (3-11a)

$$E_{\Theta m} = -E_m \cos \Theta_E \qquad (3-11b)$$

$$E_{\phi m} = -E_{m} \sin \Theta_{E} \qquad (3-11c)$$

$$\vec{k} = k \vec{r}$$

$$\vec{R} = r \vec{r} = x \vec{x} + y \vec{y} + z \vec{z}$$
(3-11d)

 \vec{R} is a vector from the origin to a point P and E_m is the magnitude of the electric field intensity. To determine the components E_{xm} , E_{ym} , E_{zm} , k_x , k_y and k_z in (3-9) we simply need the transformation from a spherical co-ordinate system to a rectangular coordinate system (see reference [12], p.9). Employing this conversion of coordinate systems, we find

$$E_{xm} = -E_{m} \cos \Theta_{E} \cos \Theta_{p} \sin \phi_{p} - E_{m} \sin \Theta_{E} \cos \phi_{p} \quad (3-12a)$$

$$E_{ym} = E_{m} \cos \Theta_{E} \sin \Theta_{p}$$
(3-12b)

$$E_{zm} = -E_{m} \cos \Theta_{E} \cos \Theta_{p} \cos \phi_{p} + E_{m} \sin \Theta_{E} \sin \phi_{p} \quad (3-12c)$$

$$k_{x} = k \sin \Theta_{p} \sin \phi_{p} \qquad (3-12d)$$

$$c_y = k \cos \Theta_p \tag{3-12e}$$

$$k_{z} = k \sin \Theta \cos \phi_{p} \qquad (3-12f)$$

Calculation of the quantities in (3-8) proceeds as follows. The i-th entry in the nxl vector M is

$$[\underline{M}]_{i} = \int_{0}^{\mathbf{L}} \cos(k(\mathbf{J} - \mathbf{x})) \{ E_{\ell_{1}}(d_{10}, \mathbf{x}) - E_{\ell_{1}}(0, \mathbf{x}) \} d\mathbf{x}$$
(3-13)

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where

(inc) (inc)

$$E_{li}(d_{10},x) - E_{li}(0,x) = E_{x}|_{y=y_{1}} - E_{x}|_{z=0}$$

 $z=z_{1}$
(3-14)
 $= E_{xm} e^{-jk_{x}x} \{e^{-j(k_{y} y_{1} + k_{z} z_{1})} - 1\}$

and the i-th wire has y and z coordinates of y_i and z_i , respectively. Substituting (3-14) into (3-13) one can obtain

$$\begin{bmatrix} \underline{M} \end{bmatrix}_{i} = E_{xm} \{ e^{-j(k_{y} y_{i} + k_{z} z_{i})} - 1 \} \int_{0}^{\mathcal{L}} \cos(k(\mathcal{L} - x)) e^{-jk_{x}x} dx$$

$$= E_{xm} \{ e^{-j(k_{y} y_{i} + k_{z} z_{i})} - 1 \} \{ \frac{e^{jk\mathcal{L}}}{2} \int_{0}^{\mathcal{L}} e^{-j(k + k_{x})x} dx$$

$$+ \frac{e^{-jk\mathcal{L}}}{2} \int_{0}^{\mathcal{L}} e^{j(k - k_{x}) x} dx \}$$
(3-15)

This result can be written in terms of the basic intergral E2 in Section 3.1 as

$$\begin{bmatrix} \underline{M} \end{bmatrix}_{i} = \frac{E_{xm}}{2} \{ e^{-j(k_{y} y_{i} + k_{z} z_{i})} - 1 \} \{ e^{jkz} E2(0, z, -(k + k_{x})) + e^{-jkz} E2(0, z, (k - k_{x})) \}$$
(3-16)

Similarly the entries in the $n\chi 1$ vector \underline{N} become

$$\begin{bmatrix} N \\ i \end{bmatrix}_{i} = \int_{0}^{\chi} \sin(k(\chi - x)) \{ E_{li}(d_{10}, x) - E_{li}(0, x) \} dx$$

$$= -j \frac{E_{xm}}{2} \{ e^{-j(k_{y}y_{i} + k_{z}z_{i})} - 1 \} \{ e^{jk\chi} E2(0, \chi, -(k + k_{x})) - e^{-jk\chi} E2(0, \chi, (k - k_{x})) \}$$
(3-17)

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(inc) (inc) The calculation of the entries in the vectors $\underset{t}{E}_{t}(\mathbf{x})$ and $\underset{t}{E}_{t}(0)$ (inc) proceeds as follows. The i-th entry in $\underset{t}{E}_{t}(\mathbf{x})$ is given by

$$\begin{bmatrix} (inc) \\ [E_{t}(\mathbf{x})]_{i} \end{bmatrix} = \int_{0}^{d_{i0}} \begin{bmatrix} (inc) \\ E_{ti}(\rho_{i}, \mathbf{x}) \end{bmatrix} d\rho_{i}$$
(3-18)

where ρ_{1} is a straight-line contour in the y,z plane (at x=2) joining the reference wire and the i-th wire. The i-th wire is located at y=y₁, z=z₁ and the reference wire is located at y=0, z=0. The center-to-center separation between the reference wire and the i-th wire is $d_{10} = \sqrt{y_{1}^{2}+z_{1}^{2}}$. Consider Figure 3-3 which shows this contour and the appropriate components of the electric field along this contour. For this situation, (3-18) becomes

$$\begin{bmatrix} (inc) \\ [\underline{E}_{t}(\boldsymbol{\chi})]_{i} = \int_{0}^{d} \begin{bmatrix} 0 \\ (\underline{E}_{ym} \cos \theta + \underline{E}_{zm} \sin \theta) e^{-jk} \boldsymbol{\chi}^{\boldsymbol{\chi}} \\ 0 \\ \{e^{-j(k_{y}} \cos \theta + k_{z} \sin \theta) \rho_{i}\} d\rho_{i} \end{bmatrix} d\rho_{i}$$
(3-19)

where

$$\cos \Theta = \frac{y_i}{d_{10}}$$
(3-20a)

$$\sin 0 = \frac{z_1}{d_{10}}$$
 (3-20b)

Therefore, we obtain

$$\begin{bmatrix} (inc) \\ [E_{t}(\mathbf{I})]_{i} = (E_{ym} y_{i} + E_{zm} z_{i}) e^{-jk_{x}\mathbf{I}} \frac{(e^{-j(k_{y} y_{i} + k_{z} z_{i}) - 1)}}{-j(k_{y} y_{i} + k_{z} z_{i})}$$
(3-21)

This result may be written equivalently in terms of fundamental integral E2

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Figure 3-3.

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$$[\underline{E}_{t}(\mathbf{x})]_{i} = [\underline{E}_{ym} y_{i} + \underline{E}_{zm} z_{i}] e^{-jk_{x} \mathbf{x}} E2(0, 1; (k_{y} y_{i} + k_{z} z_{i}))$$
 (3-22)

(inc) The i-th entry in the vector $\underline{E}_t(0)$ is given by (3-22) with $\mathcal{L} = 0$.

3.3 Derivation of the Source Vectors for Uniform Plane Wave Illumination and TYPE 2 Structures

(inc) (inc) Derivation of the source vectors, \underline{M} , \underline{N} , $\underline{E}_y(0)$, $\underline{E}_t(\mathbf{x})$, in (3-2) and (3-4) for uniform plane wave illumination of n wires above a ground plane (TYPE 2 structures) proceeds similarly. Here, we will determine $\mathbf{\vec{E}}^{(\text{inc})}$ as the net electric field which is the vector sum of the incident wave and the wave reflected by the perfectly conducting ground plane. In this case, the net electric field tangent to the ground plane will be zero. Therefore (inc) $\underline{E}_{k1}(0,\mathbf{x})$ in (2-49a) will be zero. Again, an arbitrary rectangular coordinate system is used to define the cross-sectional positions of the wires. The ground plane forms the x,z plane (y=0) as shown in Figure 3-4. The zero phase reference for the incident field will be taken to be at the origin of this coordinate system, i.e., x=0, y=0, z=0. The various angles defining the direction of propagation of the incident wave and polarization of the electric field intensity vector are the same as for TYPE 1 structures and are shown in Figure 3-2.

The primary problem here is to determine the net electric field parallel to the wire axes and between the i-th wire and the ground plane along a contour perpendicular to the ground plane. This net electric field is the vector sum of the incident field (in the absence of the ground plane) and the portion reflected by the ground plane.

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Figure 3-4. The TYPE 2 structure.

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We may write the incident electric field

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$$\vec{E}^{i} = (E^{i}_{xm} \vec{x} + E^{i}_{ym} \vec{y} + E^{i}_{zm} \vec{z}) e^{-j(k} x + k y + k z^{2})$$
(3-23)

The angle of reflection between the reflected wave and the ground plane is equal to the angle of incidence by Snell's Law [12]. Therefore we may immediately write the form of the reflected wave as

$$\vec{E}^{r} = (\vec{E}_{xm}^{r} \vec{x} + \vec{E}_{ym}^{r} \vec{y} + \vec{E}_{zm}^{r} \vec{z}) e^{-j(\vec{k}_{x} \cdot x - \vec{k}_{y} \cdot y + \vec{k}_{z} \cdot z)}$$
(3-24)

At y=0, continuity of the tangential components of the electric field require that

$$E_{xm}^{r} = -E_{xm}^{i} \stackrel{\Delta}{=} -E_{xm}$$
(3-25a)

$$E_{zm}^{r} = -E_{zm}^{i} \stackrel{\Delta}{=} -E_{zm}$$
(3-25b)

Consequently, the net x component of the electric field is given by

$$E_{x_{Total}} = E_{xm}^{i} e^{-j(k_{x} x + k_{y} y + k_{z} z)} + E_{xm}^{r} e^{-j(k_{x} x - k_{y} y + k_{z} z)}$$
$$= E_{xm} e^{-j(k_{x} x + k_{z} z)} \{ e^{-jk_{y}y} - e^{jk_{y}y} \}$$
(3-26)
$$= -2j E_{xm} \sin(k_{y} y) e^{-j(k_{x} x + k_{z} z)}$$

where E_{xm} is the magnitude c? the x component of the incident electric field, i.e., $E_{xm} \stackrel{\Delta}{=} E_{xm}^{i}$. Similarly, one may show that the net y component of the electric field is given by [12]

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$$E_{y_{\text{Total}}} = 2 E_{ym} \cos(k_{y} y) e^{-j(k_{x} x + k_{z} z)}$$
 (3-27)

The components of the $n\chi 1$ vector \underline{M} become

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$$\begin{bmatrix} \underline{M} \end{bmatrix}_{i} = \int_{0}^{\mathbf{Z}} \cos(k(\mathbf{Z} - \mathbf{x})) \begin{bmatrix} inc \\ \underline{E}_{\ell}(\mathbf{x}) \end{bmatrix}_{i} d\mathbf{x}$$

$$= \int_{0}^{\mathbf{Z}} \cos(k(\mathbf{Z} - \mathbf{x})) E_{\mathbf{x}}_{\text{Total}} | d\mathbf{x}$$

$$= \int_{0}^{\mathbf{Z}} \cos(k(\mathbf{Z} - \mathbf{x})) E_{\mathbf{x}}_{\text{Total}} | d\mathbf{x}$$

$$= \int_{0}^{\mathbf{Z}} \exp(k(\mathbf{Z} - \mathbf{x})) E_{\mathbf{x}}_{\text{Total}} | d\mathbf{x}$$

$$= \int_{0}^{\mathbf{Z}} \exp(k(\mathbf{Z} - \mathbf{x})) E_{\mathbf{x}}_{\text{Total}} | d\mathbf{x}$$

$$= -2jE_{xm} e^{-jk}z^{z}i \sin(k_{y}y_{i}) \int_{0}^{z} \cos(k(z - x))e^{-jk}x^{x} dx$$

$$= -jE_{xm} e^{-jk}z^{z}i \sin(k_{y}y_{i}) \int_{0}^{z} e^{jkz} e^{-jkx} e^{-jk}x^{x}$$

$$+ e^{-jkz} e^{jkx} e^{-jk}x^{x} dx$$

$$= -jE_{xm} e^{-jk}z^{2}i \sin(k_{y}y_{i}) \{e^{jk^{2}}E2(0, \mathbf{z}, -(k+k_{x})) + e^{-jk^{2}}E2(0, \mathbf{z}, (k-k_{x}))\}$$

Similarly calculation of the entries in \underline{N} yields

$$\begin{bmatrix} N \end{bmatrix}_{i} = \int_{0}^{\varkappa} \sin(k(\varkappa - \varkappa)) \begin{bmatrix} inc \\ E_{k}(\varkappa) \end{bmatrix}_{i} d\varkappa$$

=
$$\int_{0}^{\varkappa} \sin(k(\varkappa - \varkappa)) E_{\chi}_{\text{Total}} \Big|_{\substack{y=y \\ z=z_{1}^{i}}} d\varkappa$$
 (3-29)
=
$$-E_{\chi m} e^{-jk} z^{z} i \sin(k_{y} y_{1}) \{e^{jk\varkappa} E^{2}(0,\varkappa, -(k+k_{\chi})) -57-$$

$$-e^{-jkZ} E2(0, \chi, (k - k_{\chi}))$$
 (3-29)

(inc) The entries in $E_t(\mathbf{x})$ are given by

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(inc) The entries in $\underline{E}_t(0)$ are those of (3-30) with $\chi = 0$.

It should be noted that the above quantities can be determined in an alternate fashion. Rather than determining the net electric field as the sum of an incident and a reflected wave, simply replace the ground plane with image wires as shown in Figure 3-5. The entries in the source vectors can then be obtained by using only the incident field and treating the image

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Figure 3-5.

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of the i-th wire as the "reference" for the i-th wire as

$$\begin{bmatrix} M \end{bmatrix}_{i} = \int_{0}^{\chi} \cos(k(\chi - x)) \{ E_{x}^{(inc)} | \sup_{\substack{y=y_{i} \\ z=z_{i}^{i}}} - E_{x}^{(inc)} | \sup_{\substack{y=-y_{i} \\ z=z_{i}^{i}}} \} dx \quad (3-31a)$$

$$= \int_{0}^{\chi} \cos(k(\chi - x)) \{ E_{xm} e^{-j(k_{x} + k_{y} + k_{y} + k_{z} + z_{i})} - E_{xm} e^{-j(k_{x} + k_{y} + k_{y} + k_{z} + z_{i})} \} dx$$

$$= E_{xm} e^{-jk} z^{z} i (e^{-jk} y^{y} i - e^{jk} y^{y} i) \int_{0}^{z} \cos(k(z'-x)) e^{-jk} x^{x} dx$$

=-2j $E_{xm} e^{-jk} z^{z} i \sin(k_{y} y_{i}) \int_{0}^{z} \cos(k(z'-x)) e^{-jk} x^{x} dx$
=-j $E_{xm} e^{-jk} z^{z} i \sin(k_{y} y_{i}) \{e^{jkz} E^{2}(0, z, -(k + k_{x})) + e^{-jkz} E^{2}(0, z, -(k + k_{x}))\}$

$$\begin{bmatrix} \mathbf{N} \end{bmatrix}_{i} = \int_{0}^{\mathbf{Z}} \sin(k(\mathbf{Z} - \mathbf{x})) \begin{bmatrix} \mathbf{E}_{\mathbf{x}} & | & \mathbf{E}_{\mathbf{x}} \\ y = y_{i} \\ z = z_{i}^{i} \end{bmatrix} d\mathbf{x}$$
(3-31b)
$$= \int_{0}^{\mathbf{Z}} \sin(k(\mathbf{Z} - \mathbf{x})) \begin{bmatrix} \mathbf{E}_{\mathbf{x}\mathbf{m}} & e^{-j(\mathbf{k}_{\mathbf{x}} + \mathbf{k}_{\mathbf{y}} + \mathbf{k}_{\mathbf{y}} - \mathbf{i}_{\mathbf{x}} \\ \mathbf{E}_{\mathbf{x}\mathbf{m}} & e^{-j(\mathbf{k}_{\mathbf{x}} - \mathbf{k}_{\mathbf{y}} + \mathbf{k}_{\mathbf{y}} - \mathbf{i}_{\mathbf{x}} \\ \mathbf{E}_{\mathbf{x}\mathbf{m}} & e^{-j(\mathbf{k}_{\mathbf{x}} - \mathbf{k}_{\mathbf{y}} + \mathbf{k}_{\mathbf{y}} - \mathbf{i}_{\mathbf{x}} \\ \mathbf{E}_{\mathbf{x}\mathbf{m}} & e^{-j(\mathbf{k}_{\mathbf{x}} - \mathbf{k}_{\mathbf{y}} + \mathbf{k}_{\mathbf{y}} - \mathbf{i}_{\mathbf{x}} \\ \mathbf{E}_{\mathbf{x}\mathbf{m}} & e^{-j(\mathbf{k}_{\mathbf{x}} - \mathbf{k}_{\mathbf{y}} + \mathbf{k}_{\mathbf{y}} - \mathbf{i}_{\mathbf{x}} \\ \mathbf{E}_{\mathbf{x}\mathbf{m}} & e^{-j(\mathbf{k}_{\mathbf{x}} - \mathbf{k}_{\mathbf{y}} + \mathbf{k}_{\mathbf{y}} - \mathbf{i}_{\mathbf{x}} \\ \mathbf{E}_{\mathbf{x}\mathbf{m}} & e^{-j(\mathbf{k}_{\mathbf{x}} - \mathbf{k}_{\mathbf{y}} + \mathbf{k}_{\mathbf{y}} - \mathbf{i}_{\mathbf{x}} \\ \mathbf{E}_{\mathbf{x}\mathbf{m}} & e^{-j(\mathbf{k}_{\mathbf{x}} - \mathbf{k}_{\mathbf{y}} + \mathbf{k}_{\mathbf{y}} - \mathbf{i}_{\mathbf{x}} \\ \mathbf{E}_{\mathbf{x}\mathbf{m}} & e^{-j(\mathbf{k}_{\mathbf{x}} - \mathbf{k}_{\mathbf{y}} + \mathbf{k}_{\mathbf{y}} - \mathbf{i}_{\mathbf{x}} \\ \mathbf{E}_{\mathbf{x}\mathbf{m}} & e^{-j(\mathbf{k}_{\mathbf{x}} - \mathbf{k}_{\mathbf{y}} + \mathbf{k}_{\mathbf{x}} - \mathbf{i}_{\mathbf{x}} \\ \mathbf{E}_{\mathbf{x}\mathbf{m}} & e^{-j(\mathbf{k}_{\mathbf{x}} - \mathbf{k}_{\mathbf{y}} + \mathbf{k}_{\mathbf{x}} - \mathbf{i}_{\mathbf{x}} \\ \mathbf{E}_{\mathbf{x}\mathbf{m}} \\ \mathbf{E}_{\mathbf{x}\mathbf{m}} & e^{-j(\mathbf{k}_{\mathbf{x}} - \mathbf{k}_{\mathbf{y}} + \mathbf{k}_{\mathbf{x}} - \mathbf{i}_{\mathbf{x}} \\ \mathbf{E}_{\mathbf{x}\mathbf{m}} \\ \mathbf{E}_{\mathbf{x}\mathbf{m}} & e^{-j(\mathbf{k}_{\mathbf{x}} - \mathbf{k}_{\mathbf{y}} + \mathbf{k}_{\mathbf{x}} - \mathbf{i}_{\mathbf{x}} \\ \mathbf{E}_{\mathbf{x}\mathbf{m}} \\ \mathbf{E}_{\mathbf{x}\mathbf{m}} & e^{-j(\mathbf{k}_{\mathbf{x}} - \mathbf{k}_{\mathbf{y}} + \mathbf{k}_{\mathbf{x}} - \mathbf{i}_{\mathbf{x}} \\ \mathbf{E}_{\mathbf{x}} - \mathbf{i}_{\mathbf{x}} \\ \mathbf{E}_{\mathbf{x}} \\ \mathbf{E}_{\mathbf{x}\mathbf{m}} \\ \mathbf{E$$

$$= -E_{xm} e^{-jk} z^{z} i \sin(k_{y} y_{i}) \{ e^{jk z} E2(0, z, -(k + k_{x})) - e^{-jk z} E2(0, z, (k - k_{x})) \}$$
$$\begin{bmatrix} (\text{inc}) \\ [\frac{E}{t}(\mathbf{x})]_{1} &= \int_{-y_{1}}^{y_{1}} E_{y}^{(\text{inc})} \Big|_{x=\mathbf{x}}^{z=\mathbf{x}_{1}} dy \qquad (3-31c)$$

$$= \int_{-y_{1}}^{y_{1}} E_{ym} e^{-j(k_{x}\mathbf{x} + k_{y} y + k_{z} z_{1})} dy$$

$$= \int_{ym}^{y_{1}} e^{-jk_{x}\mathbf{x}} e^{-jk_{z}z_{1}} \int_{-y_{1}}^{y_{1}} e^{-jk_{y}y} dy$$

$$= E_{ym} e^{-jk_{x}\mathbf{x}} e^{-jk_{z}z_{1}} \left\{ \int_{0}^{0} e^{-jk_{y}y} dy + \int_{0}^{y_{1}} e^{-jk_{y}y} dy \right\}$$

$$= E_{ym} e^{-jk_{x}\mathbf{x}} e^{-jk_{z}z_{1}} \left\{ \int_{0}^{y_{1}} e^{jk_{y}y} dy + \int_{-y_{1}}^{0} e^{jk_{y}y} dy \right\}$$

$$= E_{ym} e^{-jk_{x}\mathbf{x}} e^{-jk_{z}z_{1}} \left\{ \int_{0}^{y_{1}} e^{jk_{y}y} dy + \int_{-y_{1}}^{0} e^{jk_{y}y} dy \right\}$$

$$= E_{ym} e^{-jk_{x}\mathbf{x}} e^{-jk_{z}z_{1}} \left\{ E_{2}(-y_{1},y_{1},k_{y}) \right\}$$

which are precisely the results obtained previously.

3.4 Calculation of the Source Vectors for Nonuniform Fields

Nonuniform field excitation can be specified for all structure types. The problem here, again, is to evaluate equations of the form in (3-8). This requires that we specify values (magnitude and phase) of the electric field intensity vector along the wires and reference conductor and between each wire and the reference conductor at the endpoints of the line. To accomplish this, we will specify values at a finite number of points along

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the appropriate contours and assume piecewise-linear variation of the electric field (magnitude and phase) between the specified points. This is illustrated in Figure 3-6.

For TYPE 1 strucutres, the values of \vec{E} , $E_{l0}^{(m)}$, along the reference wires (in the +x direction)at $N_{l0}^{(m)}$ + 1 points will specified as shown in Figure 3-6(a). The values of \vec{E} , $E_{l1}^{(m)}$, along the i-th wire at $N_{l1}^{(m)}$ + 1 points will be specified. The values of \vec{E} , $E_{t0}^{(m)}$ and $E_{t2}^{(m)}$, at x=0 and x=2 along a straightline contour in the y,z plane joining the reference wire and the i-th wire at $N_{t0}^{(n)}$ + 1 and $N_{t2}^{(m)}$ + 1 points, respectively, will be specified. Similar quantities will be specified for TYPE 2 and TYPE 3 structures as shown in Figure 3-6(b) and Figure 3-6(c), respectively, with the exception that \vec{E} is taken to be zero along the reference conductor for these two cases.

Piecewise-linear variation of the electric field (magnitude and phase) is assumed between these specification points as shown in Figure 3-7 where the magnitude of the appropriate component of the electric field is denoted by $|\cdot|$ and the angle is denoted by $\angle \cdot$. Thus the problem is the determination of quantities of the form in (3-8) for this piecewise-linear variation of the field. The technique is to write linear equations representing the piecewise-linear variation of the magnitude and phase of the field between successive specification points and add the appropriate integrals over the adjacent regions.

The first problem then becomes to characterize the linear magnitude and phase variation between two successive data points. Consider two successive data points, x_m and x_{m+1} , which specify the magnitude of the electric field, E_m and E_{m+1} , and phase, Θ_m and Θ_{m+1} , respectively. Knowing the end points, one can write linear equations characterizing the linear

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Figure 3-6. Nonuniform field specification for TYPE 2 Structures.



Figure 3-6. Nonuniform field specification for TYPE 3 structures.



Figure 3-7. Piecewise-linear field specification.

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behavior between these successive points as

$$|E_{m}(x)| = a_{m} x + b_{m}$$
 (3-32a)

$$\Theta_{m}(x) = c_{m} x + d_{m}$$
(3-32b)

$$a_{m} = \{ \frac{E_{m+1} - E_{m}}{x_{m+1} - x_{m}} \}$$
(3-33a)

$$b_{m} = \{\frac{E_{m} x_{m+1} - E_{m+1} x_{m}}{x_{m+1} - x_{m}}\}$$
(3-33b)

$$c_{m} = \{\frac{\Theta_{m+1} - \Theta_{m}}{x_{m+1} - x_{m}}\}$$
(3-33c)

$$d_{m} = \{\frac{\overset{\odot}{m} x_{m+1} - \overset{\odot}{m} + 1 x_{m}}{x_{m+1} - x_{m}}\}$$
(3-33d)

The electric field is then characterized by

$$E_{m}(x) = |E_{m}(x)| e^{j\Theta_{m}(x)}$$
 (3-34)

The quantities of the form in (3-8) which must be evaluated involve certain integrals involving the form (3-32). The first type is of the form in (3-8d) which can be evaluated as

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$$\int_{x_{m}}^{x_{m+1}} \cos(k(\mathbf{z} - \mathbf{x})) \{a_{m} + b_{m}\} e^{j(c_{m} + d_{m})} d\mathbf{x}$$
(3-35)
$$= e^{jd_{m}} \{a_{m} \int_{x_{m}}^{x_{m+1}} \cos(k(\mathbf{z} - \mathbf{x})) + e^{jc_{m} + d_{m}} d\mathbf{x}$$

+
$$b_{m} \int_{x_{m}}^{x_{m}+1} \cos(k(z'-x)) e^{jc_{m}x} dx$$

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$$= \frac{e^{jd_m}}{2} \{a_m e^{jk\mathbf{z}} El(x_m, x_{m+1}, c_m - k)\}$$

+
$$a_m e^{-jk\lambda} \cdot Ei(x_m, x_{m+1}, c_m+k)$$

+ $b_m e^{jk\lambda} E2(x_m, x_{m+1}, c_m-k)$

+
$$b_{m} e^{-jkZ'} E2(x_{m}, x_{m+1}, c_{m}+k)$$

The second form is similar to (3-8e) which can be evaluated as

$$\int_{x_{m}}^{x_{m+1}} \sin(k(\mathbf{x} - \mathbf{x})) \{a_{m} + b_{m}\} e^{j(c_{m} + d_{m})} d\mathbf{x}$$
(3-36)
$$= \frac{e^{jd_{m}}}{2j} \{a_{m} e^{jk\mathbf{x}} E^{j(x_{m}, x_{m+1}, c_{m}-k)}$$
$$- a_{m} e^{-jk\mathbf{x}} E^{j(x_{m}, x_{m+1}, c_{m}+k)}$$

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+
$$b_{m} e^{jkZ} E2(x_{m}, x_{m+1}, c_{m}-k)$$

- $b_{m} e^{-jkZ} E2(x_{m}, x_{m+1}, c_{m}+k)$

The third forms are similar to (3-8b) and (3-8c) which can be evaluated as

$$\int_{x_{m}}^{x_{m+1}} (a_{m} x + b_{m}) e^{j(c_{m} x + d_{m})} dx \qquad (3-37)$$

$$= e^{\int d_m} \{a_m E1(x_m, x_{m+1}, c_m)\}$$

+ $b_m E2(x_m, x_{m+1}, c_m)$ }

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The program computes the items in (2-36) and (2-37) for TYPE 1 structures; (2-49) and (2-37) for TYPE 2 structures; and (2-52) and (2-37) for TYPE 3 structures by breaking up the appropriate integrals and adding the integrals between each pair of successive data points. The data points need not be equally spaced along the appropriate contours so that one can model localized, extreme variations in the fields without using an inordinately large number of data points. In specifying the sequence of electric field components along each contour, one must insure that the first and last specification points are at the two ends of the contour and $x_m < x_{m+1}$.

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IV. COMPUTER PROGRAM DESCRIPTION

The contents and operation of the code will be described in this Chapter. The cards in the program deck are sequentially numbered in columns 73-80 with the word WIRE in 73-76 and the card number in 77-80. The program is written in Fortran IV language and is double precision. A listing of the program is contained in Appendix B and a general flow chart of the program is given in Appendix B. In this flow chart, the numbers on the left and right of the individual boxes denote the beginning and ending card numbers of the corresponding portion of the code listing, respective¹y. Changes in the program to convert to single precision arithmetic are indicated in Appendix B. The program has been implemented on an IBM 370/165 digital computer at the University of Kentucky using the Fortran IV G-Level compiler.

The program requires two function subprograms, El and E2, and one subroutine, LEQTIC, which must follow the main program and precede the data cards. Subroutine LEQTIC is a general purpose subroutine to solve a set of n, complex, linear simultaneous equations and is a part of the IMSL (International Mathematical and Statistical Library) package [13]. If the IMSL package is not available on the ver's system, other appropriate general purpose subroutines may be used. (See Section 4.2 for a discussion of LEQTIC and its argument list.) Listings of function subprograms E1 and E2 are contained in Appendix C.

4.1 Main Program Description

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A listing of the WIRE program is contained in Appendix B. Cards 0001 through 0055 contain general comments concerning the applicability of the

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program. Cards 0057 through 0060 contain the array dimension information. All vectors and matrices should be dimensioned to be of size N where N is the number of wires exclusive of the reference conductor. These matrices and vectors must be dimensioned appropriately for each problem. Cards 0062 through 0069 declare double precision real and complex variables and dimension the vector and matrix arrays.

Cards 0071 through 0080 define certain constants,

CMTM (conversion from mils to meters)	=	2.54×10^{-5}
MU02PI	ux	μ/2π
ONE	=	1.
P5	-	• 5
FOUR	×	4.
ONE80	**	180.
7£30	-	0.
7 \ \'L	*	2.
ONEC	*	1. + j0.
ZEROC	*	0. + j0.
XJ	=	0. + j1.
V(velocity of light in ree space)	-	2.997925 x 10^8 m/sec
PI	*	π
RADEG(conversion from radians to degrees)	*	180./π

Note that π is computed to the user's machine precision by using the relationship

 $\tan (\pi/4) = 1$

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Cards 0086 through 0145 read and print portions of the input data and perform certain primitive error checks. These cards read the structure type (TYPE=1,2,or3), the load specification option (LSO=11,12,21,or22), the field specification option (FSO=1,or2), the number of wires, N, the relative permittivity of the medium, ER, the relative permeability of the medium, MUR, and the line length, L. In addition, for TYPE 1 structures, the radius of the reference wire, RWO, and for TYPE 3 structures, the interior radius of the overall, cylindrical shield, RS, are read.

Cards 0150 through 0197 read the radii, r_{wi} , and the z_i and y_i coordinates (r_i and Θ_i for TYPE 3) for the N wires and compute the entries in the characteristic impedance matrix. The z and y coordinates are stored in the real, n_X , vectors V3 and V4, respectively:

$$\left\{ \begin{array}{c} z_{i} \text{ for TYPE 1,2} \\ r_{i} \text{ for TYPE 3} \end{array} \right\} + V3(I)$$

 $\left\{ \begin{array}{l} y_i \text{ for TYPE 1,2} \\ \Theta_i \text{ for TYPE 3} \end{array} \right\} \rightarrow V4(I)$

In addition, the entries in the $n\chi n$, real characteristic impedance matrix, Z_{c} , are temporarily stored in the real parts of the $n\chi n$ complex matrix M1. This is done to minimize the required array storage in the program since the matrix M1 will be needed later as a complex matrix.



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Cards 0202 through 0211 compute the inverse of Z_{C} , Z_{C}^{-1} , which is stored in the real parts of the n χ n, complex arrays M2 and M3. Subroutine LEQTIC computes this inverse by solving the system of equations AX = 1where 1_n is the n χ n identity matrix. The solution X is therefore A^{-1} . (See Section 4.2 for a more complete discussion of subroutine LEQTIC.) Since the real part of M1 contains the characteristic impedance matrix, the real part of the n χ n, complex solution matrix, M2, will contain Z_{C}^{-1} . Therefore

Matrix	Array
z_c^{-1}	M2 (real part)
z_{c}^{-1}	M3 (real part)

Cards 0222 through 0254 read and print the entries in the terminal impedance (admittance) matrices at x = 0, Z_0 (Y_0), and at x = I, Z_I (Y_I). These are stored in the nxn, complex arrays as

<u> Thevenin Equivalent</u>	Norton Equivalent	<u>Array</u>
z _o	¥_0	YO
^Z £	۲ ۲	YL

Cards 0259 through 0267 interchange the entries in arrays M1 and M2 if the Thevenin equivalent characterization is chosen. Thus

Thevenin Equivalent	Norton Equivalent	Array
z_{c}^{-1}	^z c	Ml
^Z c	z_{c}^{-1}	M2
z_{c}^{-1}		M3

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Cards 0273 through 0292 compute the quantities:

Thevenin Equivalent	Norton Equivalent	Array
$z_{\rm C} + z_{\rm C} z_{\rm C}^{-1} z_{\rm C}$	$\frac{Y}{2}$ $\frac{Z}{C}$ $\frac{Y}{20}$ + $\frac{Z}{2C}$ -1	M2

The contents of this array M2 will be retained throughout any frequency iteration so that these matrix products need be computed only once.

Cards 0293 and 0294 compute the phase constant for a frequency of one hertz and its product with the line length:

Quantity

Variable

BB

 $\left| k \right|_{1 \text{ Hertz}} = \frac{2\pi}{(v_0/\sqrt{\mu_r \varepsilon_r})}$

To obtain the propagation constant at each frequency, BB is multiplied by the appropriate frequency.

Cards 0300 through 0323 read the input data describing the uniform plane wave if FSO = 1, i.e., E_m , Θ_E , Θ_p , ϕ_p , and compute the x, y, z components of the electric field and propagation constant (for one Hertz) as shown in (3-12).

Cards 0327 through 0333 read the frequency on the first frequency card and compute the propagation constant, k, k ℓ , sin(k χ), cos(k χ):

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Quantity	Variable	
k	BETA	
k L	BETAL	
sin(k 1)	DS	
cos (k 🗶	DC	

If uniform plane wave field specification is selected (FSO = 1), cards 0342 through 0351 compute certain preliminary quantities to be used in (inc) (inc) computing the induced source vectors \underline{M} , \underline{N} , $\underline{E}_{t}(0)$, $\underline{E}_{t}(\mathbf{f})$. If TYPE 1 structures are selected, cards 0357 through 0370 compute the items in these induced source vectors as:

Vector	Array
<u>M</u> (3-16)	V1
$\frac{N}{(1-2)}$	V2
$\frac{E}{(2\pi)} (0) (3-22, \mathbf{I} = 0)$	ETO
\underline{E} (z) (3-22)	ETL

If TYPE 2 structures are selected, the items in the induced source vectors are computed in cards 0375 through 0386 as;

Vector	Array
<u>M</u> (3-28)	V1
$\frac{N}{(1nc)}$ (3-29)	V2
$E_{1}(0) (3-30, \mathbf{x} = 0)$	ETO
$\underline{E}_{1}(\mathbf{z})$ (3-30)	ETL

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If nonuniform field excitation (FSO=2) is selected, cards 0399 through (inc) (inc) 0542 compute the entries in the induced source vectors M, N, $\underline{E}_{+}(0)$, $\underline{E}_{+}(\mathbf{z})$. Cards 0399 through 0439 read the magnitude and phase of the incident electric field at specification points along the reference wire and compute the portions of M and N along the reference wire if TYPE 1 structures are selected. If TYPE 2 or TYPE 3 structures are selected, this computation is bypassed since for these types of structures it is assumed that the total electric fields tangent to the ground plane and the interior wall of the cylindrical shield are zero. Cards 0444 through 0479 read the magnitude and phase of the incident electric field at specification points along the wires and compute the entries in M and N for each wire which are stored in arrays V1 and V2, respectively. (The i-th entries contain the results for the i-th wire.) Cards 0484 through 0510 read the magnitude and phase of the incident electric field at specification points along contcurs in the y, z plane between the reference conductor and the 1-th wire at x=0 and (inc) compute the entries in $\underline{E}_{+}(0)$ which are stored in array ETO. (The electric field is tangent to these contours.) Cards 0515 through 0542 repeat this (inc) calculation for x=2 and compute the entries in $\underline{E}_{t}(\mathbf{x})$ which are stored in array ETL.

Cards 0548 through 0592 form the equations

 $[\cos (kz) \{ Z_0 + Z_z \} + j \sin (kz) \{ Z_C + Z_z Z_C^{-1} Z_0 \}] \underline{I}(0) =$ $(inc) = \underline{M} + j Z_z Z_c^{-1} \underline{N} - \underline{E}_t(z) + [\cos (kz) 1_n + j \sin (kz) Z_z Z_c^{-1}] \underline{E}_t(0)$

for the Thevenin Equivalent specification (LSO=11,12) or

$$[\cos(kt) \{ Y_0 + Y_t \} + j \sin(kt) \{ Y_t Z_c Y_0 + Z_c^{-1} \}] [-V(0)] =$$

$$= Y_t M + j Z_c^{-1} N - Y_t E_t(t) + [\cos(kt) Y_t + j \sin(kt) Z_c^{-1}] E_t(0)$$
(inc)

for the Norton Equivalent specification (LSO=21,22). The coefficient matrix is stored in array A and the right-hand side vector of the equations is stored in array B. The arrays V1, V2, ETO, ETL contain

Vector	Array
(inc) $\underline{M} - \underline{E}_{t}(\mathbf{z})$	٧ı
$z_{c}^{-1} \frac{(inc)}{\underline{E}_{t}}(0)$	ETL
(inc) <u>E</u> t ⁽⁰⁾	ETO
N	V 2

The main diagonal entries in the array M1 contain Z_{C}^{-1} N

Vector

 z_{c}^{-1} <u>N</u>

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Array

M1 (cn main diagonol)

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Subroutine LEQTIC is called for the solution of these equations in card 0596 and the solution vector ($\underline{I}(0)$ for LSO=11,12 or $-\underline{V}(0)$ for LSO=21,22) is returned in array B.

The terminal currents are computed in cards 0610 through 0641. Cards 0610 through 0618 compute the quantities:

Thevenin Equivalent	Norton Equivalent	Array
$z_0 I(0)$	$\underline{I}(0) = \underline{Y}_0 [-\underline{V}(0)]$	WA

Cards 0619 through 0631 compute the terminal currents at x=Z for the Thevenin Equivalent from

$$\underline{I}(\mathbf{I}) = -j \sum_{C}^{-1} \{ \underline{N} + \sin(k\mathbf{I}) + \frac{i}{E_{t}}(0) \} + [\cos(k\mathbf{I}) + \frac{1}{2} \sin(k\mathbf{I}) + \frac{1}{2} \sin$$

and for the Norton Equivalent from

$$\underline{I}(\boldsymbol{z}) = -j \sum_{C}^{-1} \{ \underline{N} + \sin(k\boldsymbol{z}) = \underline{E}_{t}(0) \} + [\cos(k\boldsymbol{z}) = \underline{Y}_{0} + j \sin(k\boldsymbol{z}) = \underline{Z}_{C}^{-1}] [-\underline{V}(0)]$$

4.2 Subroutine LEQTIC

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Subroutine LEQTIC is a general subroutine for solving a system of n simultaneous complex equations. The program is a part of the IMSL (International Mathematical and Statistical Library) package [13].

The subroutine solves the system of equations

$$\begin{array}{c} A X = B \\ \tilde{} & \tilde{} \end{array} \tag{4-1}$$

where A is an nxn complex matrix, B is an nxm complex matrix and X is an \tilde{x}_i , are solutions to

$$A X_{i} = B_{i}$$
(4-2)

where \underline{B}_i is the i-th column of B.

The calling statement is

where

 $A \rightarrow A$ $B \rightarrow B$ \sim $N \rightarrow n$ $M \rightarrow m$

and WA is a complex working vector of length n. IER is an error parameter which is returned as $^{l} \label{eq:which}$

IER = $128 \rightarrow \text{no solution error}$ IER = $129 \rightarrow \text{A}$ is algorithmically singular [13].

The solution X is returned in array B and the contents of array A are destroyed.

Subroutine LEQTIC can be used to find the inverse of an nxn matrix by computing

$$\begin{array}{l} A X = 1 \\ a x = -n \end{array}$$
(4-3)

where l_{n} is the nxn identity matrix. Thus the solution is $X = A^{-1}$. LEQTIC is used in numerous places to invert real matrices by defining the real part of A to be the matrix and the imaginary part to be zero. Upon solution, the real part of X is the inverse of the real matrix, A.

4.3 Function Subprograms El and E2

Function subprograms El and E2 are used to evaluate (in closed form) the

¹ The solution error parameter is printed out whenever A is singular. The error is IER-128 so that the solution error will be 1°when A is singular.

commonly occurring integrals:¹

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El (a,b,k) =
$$\int_{a}^{b} x e^{jkx} dx$$
 (4-4)

E2 (a,b,k) =
$$\int_{a}^{b} e^{jkx} dx$$
 (4-5)

Function E2 can be evaluated as

E2 (a,b,k) =
$$\frac{e^{jkb} - e^{jka}}{jk}$$
 (4-6)

which can be written in an alternate form as

$$E2 (a,b,k) = e^{\frac{jk(b+a)}{2}} (4-7)$$

$$= e^{\frac{jk(b+a)}{2}} \frac{\frac{jk(b-a)}{2} - \frac{jk(b-a)}{2}}{\frac{jk(b-a)}{2}}$$
$$= (b-a) \frac{\frac{sin\{\frac{k(b-a)}{2}\}}{\frac{k(b-a)}{2}}}{\frac{jk(b-a)}{2}} e^{\frac{jk(b+a)}{2}}$$

This form of E2 is more attractive from a computational standpoint since the $\sin(X)/X$ expression in the final result can be computed quite accurately for small values of the argument whereas the form in (4-6) may suffer from roundoff errors when k is small. In fact, a test was conducted on the IBM 370/165 in double precision by computing the function $\sin(X)/X$ for values of X=1, .1, .01, .001, ---, 10^{-78} until exponential underflow occurred. The results converged to the expected value of 1. In fact, for values of X from 10^{-8} to 10^{-78} the result was $\frac{.93-----9}{.15 \text{ digits}}$.

Note that these integrals can be analogously viewed as Fourier Transforms. Although this concept is interesting, it provides no significant help since the evaluation of these integrals can be easily obtained in a straightforward manner without resorting to a table of transforms.

The function E2 is computed in the function subprogram E2 with argument list

The quantity DIF=B-A is computed as well as the quantities $FA=\frac{X}{2}$ DIF and $FB=\frac{X}{2}$ (B+A). If FA=0, the program evaluates E2=DIF since sin(FA)/FA = 1. If not, the program evaluates E2=DIF {sin(FA)/FA} e^{jFB}.

Finding a more suitable computational form for El is considerably more complicated. El can be evaluated as

$$E1 (a,b,k) = \int_{a}^{b} xe^{jkx} dx \qquad (4-8)$$



This result can be separated into a real and imaginary part, i.e.,

$$E1(a, b, k) = RE + j IM$$
 (4-9)

where

$$RE = \frac{\cos(kb) + kb \sin(kb) - \cos(ka) - ka \sin(ka)}{k^2}$$
(4-10a)

$$\frac{\sin(kb) - kb \cos(kb) - \sin(ka) + ka \cos(ka)}{k^2}$$
 (4-10b)

The real part can be written as

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$$RE = \frac{1}{k^2} \left[2 \sin\left\{\frac{k(b+a)}{2}\right\} \sin\left\{\frac{k(a-b)}{2}\right\} \right]$$
(4-11)

$$+ \frac{b \sin(kb) - a \sin(ka)}{k}$$

$$= - \frac{(b^{2} - a^{2})}{2} \left[\frac{\sin\{\frac{k(b+a)}{2}\}}{\frac{k(b+a)}{2}} \frac{\sin\{\frac{k(b-a)}{2}\}}{\frac{k(b-a)}{2}} \right]$$

$$+ b^2 \frac{\sin(kb)}{kb} - a^2 \frac{\sin(ka)}{ka}$$

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Note that this form of the real part of El contains only $\sin(X)/X$ expressions and can be computed very accurately for small X. Notice that as $k \rightarrow 0$, the real part becomes

$$\frac{RE}{k+0} = \frac{b^2 - a^2}{2}$$
(4-12)

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which is precisely the value of El(a, b, k) when k=0. Therefore the imaginary part of El must go to zero as k goes to zero.

The imaginary part of El can be written as

$$IM = \frac{\sin(kb) - kb \cos(kb) - \sin(ka) + ka \cos(ka)}{k^2}$$
(4-13)
= $\frac{a \{ \cos(ka) - \frac{\sin(ka)}{ka} \} - b \{ \cos(kb) - \frac{\sin(kb)}{kb} \}}{k}$

Note that as $k \rightarrow 0$ there is a distinct possibility of roundoff error in computing the function

$$\cos(\vartheta) - \frac{\sin(\vartheta)}{\vartheta} \tag{4-14}$$

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$$RE = \frac{1}{k^2} \left[2 \sin\left\{\frac{k(b+a)}{2}\right\} \sin\left\{\frac{k(a-b)}{2}\right\} \right]$$
(4-11)

$$+ \frac{b \sin(kb) - a \sin(ka)}{k}$$

$$= - \frac{(b^{2} - a^{2})}{2} \left[\frac{\sin\{\frac{k(b+a)}{2}\}}{\frac{k(b+a)}{2}} \frac{\sin\{\frac{k(b-a)}{2}\}}{\frac{k(b-a)}{2}} \right]$$

$$+ b^2 \frac{\sin(kb)}{kb} - a^2 \frac{\sin(ka)}{ka}$$

Note that this form of the real part of El contains only $\sin(X)/X$ expressions and can be computed very accurately for small X. Notice that as $k \rightarrow 0$, the real part becomes

$$RE = \frac{b^2 - a^2}{2}$$
(4-12)

which is precisely the value of El(a, b, k) when k=0. Therefore the imaginary part of El must go to zero as k goes to zero.

The imaginary part of El can be written as

$$IM = \frac{\sin(kb) - kb \cos(kb) - \sin(ka) + ka \cos(ka)}{k^2}$$

$$= \frac{a \{ \cos(ka) - \frac{\sin(ka)}{ka} \} - b \{ \cos(kb) - \frac{\sin(kb)}{kb} \}}{k}$$

Note that as k+O there is a distinct possibility of roundoff error in computing the function

$$\cos(\vartheta) - \frac{\sin(\vartheta)}{\vartheta}$$
 (4-14)

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converges to 1. Clearly, as k+0, the imaginary part of E1, IM, converges to zero, as expected.

We will select a value of $|0| = .01 = .573^{\circ}$ as the point below which we evaluate a truncated portion of (4-16). The tradeoff here is to select a value of |0| small enough so that a truncated portion of (4-16) will not require many terms for sufficient accuracy yet |0| is not too small to result in round off error when evaluating (4-13) directly. We have selected the value to be |0| = .01 and will truncate the series in (4-16) to

$$(1 - \frac{\omega^2}{10})$$
 (4-17)

For |0| = .01, the cos 0 and $\frac{\sin \theta}{\theta}$ terms in (4-14) are identical to only 4 digits. This should provide sufficient accuracy to prevent any significant roundoff error in (4-14). In evaluating (4-16), we will obtain accuracy to 10 digits by using the truncation in (4-17). (Note, for $0 = .01, 0^2/10=10^{-5}$, $0^4/280 = 3.57 \times 10^{-11}$, $0^6/15120 = 6.61 \times 10^{-17}$, and terms with higher powers of θ affect only those digits well to the right of 16 places.) Thus this criterion seems to provide sufficient accuracy while limiting the roundoff error in evaluating IM. Therefore, our result is

$$IM = IMA - IMB \tag{4-18}$$

where

IMA =
$$\frac{a}{k} \{ \cos(ka) - \frac{\sin(ka)}{ka} \} |ka| > .01$$
 (4-19a)
= $-\frac{ka^3}{3} \{ 1 - \frac{(ka)^2}{10} \} |ka| \le .01$

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IMB =
$$\frac{b}{k} \{ \cos(kb) - \frac{\sin(kb)}{kb} \} |kb| > .01$$
 (4-19b)

$$= -\frac{kb^{3}}{3} \{ 1 - \frac{(ka)^{2}}{10} \} \qquad |kb| \leq .01$$

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IMB =
$$\frac{b}{k} \{ \cos(kb) - \frac{\sin(kb)}{kb} \} |kb| > .01$$
 (4-19b)

$$= -\frac{kb^{3}}{3} \{ 1 - \frac{(ka)^{2}}{10} \} \qquad |kb| \leq .01$$

5.1 Transmission Line Structure Characteristics Cards, Group I

WIRE considers (n+1) conductor transmission lines consisting of n wires in a lossless, homogeneous surrounding medium and a reference conductor for the line voltages. The n wires and the reference conductor are considered to be perfect (lossless) conductors. There are three choices for the reference conductor type:

TYPE = 1	: The refere	nce conductor	is a	a wire.
TYPE = 2	: The refere	nce conductor	is a	an infinite
	ground pla	ne.		
TYPE = 3	: The refere	nce conductor	is a	an overall,
	cylindrica	l shield.		

Cross-sectional views of each of these three structure types are shown in Figure 5-1, 5-2 and 5-3, respectively.

For the TYPE 1 structure shown in Figure 5-1, an arbitrary rectangular coordinate system is established with the center of the coordinate system at the center of the reference conductor. The radii of all (n+1) wires, r_{wi} , as well as the Z and Y coordinates of each of the n wires serve to completely describe the structure. Negative coordinate values must be input as negative data items. For example, Z_i and Y_j in Figure 5-1 would be negative numbers.

For the TYPE 2 struc re shown in Figure 5-2, an arbitrary coordinate system is established with the ground plane as the 2 axis. The coordinates Y_i and Y_j (positive quantities) define the heights of the i-th and j-th wires, respectively, above the ground plane. The necessary data are the

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Figure 5-3. The TYPE 3 structure.

Z and Y coordinates and the radius, r_{wi} , of each wire.

For the TYPE 3 structure shown in Figure 5-3, an arbitrary cylindrical coordinate system is established with the center of the coordinate system at the center of the shield. The necessary parameters are the radii of the wires, r_{wi} , the angular position, θ_i , the radial position, r_i , of each wire and the interior radius of the shield, r_e .

The format of the structural characteristics cards, Group I, is shown in TABLE 1. The first card contains the structure TYPE number (1, 2, or 3), the load structure option number, LSO, (11, 1^o, 21, or 22), the field specification option number, FSO, (1 or 2), the number of wires, n, the relative dielectric constant of the surrounding medium (homogeneous), e_r , the relative permeability of the surrounding medium (homogeneous), μ_r , and the total length of the transmission line, \mathbf{Z} , (meters). If TYPE 1 or 3 is selected, a second card is required which contains the radius of the reference wire, r_{w0} , (mils) for TYPE 1 structures or the interior radius of the shield, r_s , (meters) for TYPE 3 structures. For TYPE 2 structures, this card is absent. These cards are followed by n cards each of which contain the radii of the n wires, r_{w1} , (mils) and the Z_1 and Y_1 coordinates of each wire (meters) for TYPE 1 and 2 structures or the angular coordinates r_1 (meters) and Θ_1 (degrees) of the i-th wire for TYPE 3 structures. These n cards must be arranged in the order i = 1, i = 2, ---, i = n.

5.2 The Termination Network Characterization Cards, Group II

This group of cards conveys the terminal characteristics of the termination networks at the ends of the line, x = 0 and x = I. The termina 'on networks are characterized by either the Thevenin Equivalent or the Norton

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<u>Card</u>	Group #1 (total = 1):	card column	format
(a)	TYPE (1,2,3)	10	1
(b)	LOAD STRUCTURE OPTION, LSO, (11,12,21, or 22)	19 - 20	I
(c)	FIELD SPECIFICATION OPTION, FSO, (1 or 2)	30	I
(d)	n (number of wires)	39 - 40	I
(e)	ε (relative dielectric r constant of the surrounding medium)	41 - 50	E
(f)	r surrounding medium)	51 - 60	Е
(g)	\mathbf{I} (line length in <u>meters</u>)	61 - 70	E
Card	Group #2 ($total = 1$ if TYPE = 1 or 3) total = 0 if TYPE = 2)		
(a)	$T/PE = 1: r_{w0}$ (radius of reference) wire in mils	6 - 1.5	E
(b)	TYPE = 2: absent		
(c)	TYPE = 3: r _s (interior radius of) shield in <u>meters</u>)	6 - 15	E
Card	Group #3 (total = n)		
(a)	r _{wi} (wire radius in <u>mils</u>)	6 - 15	E
(b)	Z _i for TYPE 1 or 2 in <u>meters</u>	21 - 30	E
	r for TYPE 3 in meters		
(c)	Y for TYPE 1 or 2 in meters	36 - 45	E
	O for TYPE 3 in degrees		
Note	Cards in Group #3 must be arranged in t wire 1, wire 2,, wire n	he ord er:	

TABLE 1

Format of the Structure Characteristics Cards, Group I

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Equivalent characterization. These characterizations are of the form

 $\frac{V(0) = -Z_0 I(0)}{V(1) = Z_1 I(1)}$ The venin
(5-1a) $\frac{V(1) = Z_1 I(1)}{Z_1 I(1)}$ Equivalent

$$\underline{I}(0) = -\underline{Y}_{0} \underline{V}(0)$$
Norton
$$\underline{I}(\mathbf{z}) = \underline{Y}_{\mathbf{z}} \underline{V}(\mathbf{z})$$
Equivalent
(5-1b)

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(See Volume VII or Chapter II for a more complete discussion of determining the entries in Z_0 , Z_{\pm} , Y_0 and Y_{\pm} [2].) The transmission line consists of n wires which are numbered from 1 to n and a reference conductor for the line voltages. The reference conductor is numbered as the zero (0) conductor. Thus Z_0 , Z_{\pm} , Y_0 , V_{\pm} are nxn matrices which are assumed to be symmetric. The n entries in each of the nxn vectors, V(0) and $V(\pm)$, are the line voltages with respect to the reference conductor at x=0 and x= \pm , respectively. The n entries in each of the nxn vectors, I(0) and $I(\pm)$, are the line currents at x=0 and x= \pm , respectively. The currents at x=0 are directed out of the termination networks whereas the currents at x= \pm are directed into the termination networks. The entries in these four vectors are arranged in the order wire 1, wire 2, ----, wire n.

The impedance or admittance matrices, Z_{0} and Z_{0} or Y_{0} and Y_{2} , respectively, may either be "full" in which all entries are not necessarily zero or may be diagonal in which only the entries on the main diagonals are not necessarily zero and the off-diagonal entries are zero. The user may select one of four LOAD STRUCTURE OPTIONS (LSO) for communicating the

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entries in the vectors and matrices in (5-1). These are:

LSO = 11	{ The venin Equivalent representation; { diagonal impedance matrices, Z_0 and Z_1 . }
LSO = 12	{ The venin Equivalent representation; full impedance matrices, Z_0 and Z_{1} . }
LSO = 21	{ Norton Equivalent representation; { diagonal admittance matrices, Y_{0} and Y_{1} .}
LSO = 22	$ \left\{ \begin{array}{l} \text{Norton Equivalent representation;} \\ \text{full admittance matrices, } \begin{array}{l} Y_{0} \\ \text{and } \begin{array}{l} Y_{1} \end{array} \right\} $

The structure and ordering of the data in Group II are given in Table 2 and can be summarized in the following manner. The first group of cards in Group II, Group II(a), will describe the entries on the main diagonal in $Y_0(Z_0)$, $Y_{011}(Z_{011})$, and $Y_{-1}(Z_1)$, $Y_{111}(Z_{11})$. These cards must be in the order from i = 1 to i = n. Each of these entries is in general, complex. Therefore two card blocks are assigned for each entry; one for the real part and one for the imaginary part. For example, consider a 4 conductor line (3 wires and a reference conductor). Here n would be 3. Suppose the Thevenin Equivalent correcterization is selected, with the following entries in the characterization matrices:

$$Z_0 = \begin{bmatrix} 7 + j8 & 0 & 0 \\ 0 & j9 & 0 \\ 0 & 0 & 10 + j11 \end{bmatrix}$$

$$\mathbf{Z}_{\mathbf{f}} = \begin{bmatrix} 16 & 0 & 0 \\ 0 & 17 + \mathbf{j} \mathbf{18} & 0 \\ 0 & 0 & \mathbf{j} \mathbf{19} \end{bmatrix}$$

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TABLE 2 (continued)

Format of the Termination Network Characterization Cards, Group II

	Group II(a)	(total = n)	
		card column	format
Y ₀₁₁ (Z ₀₁₁)	<pre>{ real part</pre>	1 - 10	E
	(imaginary part	11 - 20	E
^Y Z11 ^{(Z} Z11)	<pre>{ real part</pre>	41 - 50	E
	(imaginary part	51 - 60	E

Note: A total of n cards must be present for an n wire line and must be arranged in the order:

wire 1 wire 2 ... wire n



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TABLE	2
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Group II(b) $\binom{\text{total} = n(n-1)/2 \text{ if OPTION} = 12 \text{ or } 22}{\text{total} = 0 \text{ if OPTION} = 11 \text{ or } 21}$

		card column	format
Y _{01j} (Z _{01j})	∫rea⊥ part	1 - 10	E
	(imaginary part	11 - 20	E
Y _{Lij} (Z _{Lij})	<pre>f real part</pre>	41 - 50	E
	(imaginary part	51 - 60	E

<u>Note</u>: If LSO = 12 or 22, a total of n(u-1)/2 cards must be present and must follow Group II(a). If LSO = 11 or 21, this card group is omitted. The cards must be arranged so as to describe the entries in the upper triangle portion of $Y_0(Z_0)$ and $Y_1(Z_1)$ by rows, i.e., the cards must contain the 12 entries, the 13 entries, ---, the ln entries, the 23 entries, ---, the 2n entries, --- etc. The ordering of the cards is therefore:

wires 1,2 wires 1,3 wires l,n wires 2,3 wires 2,4

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One would have selected LSO=11. The n=3 cards would be arranged (in this order)

~	7.E0	8.E0	16.E0	0.E0
II(a)	0.E0	9.E0	17.EO	18.E0
	10.E0	11.E0	0.E0	19.E0
Card	` io	žo	50	60

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If the terminal impedance matrices were not diagonal, e.g., LSO=12 is selected, then n(n-1)/2 additional cards, Group II(b), would follow the above n cards comprising Group II(a). These cards describe the entries in the upper triangle portion of the termination impedance or admittance matrices by rows. Suppose the networks are characterized by the Z and Z matrices:

	7 + j 8	20 + j21	22 + j23
Z ₀ =	20 + 323	<u>1</u> 9	24 + j25
	22 + j23	24 + j25	10 + j11
	16	26 + j27	28
Z_z=	26 + j27	17 + j18	j29
	28	j29	j19

The following n(n-1)/2 = 3 cards must follow the above 3 cards in the order of the 12 entries first, the 13 entries next and then the 23 entries:

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column	10	20	50	60
Card	\ +	+	t	+
	24.E0	25.E0	0.E0	29.EO
Group II(b)	22.E0	23.E0	28.E0	0.E0
	20.E0	21.EO	26.E0	27.EO

5.3 The Field Specification Cards, Group III

There are two Field Specification Options (FSO) for specifying the form of the excitation field:

FSO = 1 { Uniform plane wave illumination of the line(TYPE1 or TYPE 2 structures only)

5.3.1 Uniform Plane Wave Illumination, FSO=1

For uniform plane wave illumination of the line, FSO=1, the format of the data cards is shown in Table 3 and consists of two card groups. Card Group #1 consists of one card containing the magnitude of the electric field intensity vector, E_m , the angle between this vector and the projection of the y axis on the plane containing \vec{E} (this plane is perpendicular to the propagation direction), the angle between the y axis and the direction of propagation, and the angle between the z axis and the projection of the propagation vector onto the x,z plane. (See Figure 5-4.) The x coordinate is parallel to the n wires and reference conductor, and the y,z plane forms the cross-section of the line. The origin of the coordinate system,

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TABLE 3

Format of the Field Specification Cards, Gro	oup III, for Uniform	Plane Wave
Illumination, FSO=1,	(See Figure 5-4)	
Card Group #1 (total = 1):	card column	format
(a) E (magnitude of the electric field m intensity vector in <u>volts/meter</u>)	1 - 10	E
(b) ^O E (angle of electric field intensity vector in <u>degrees</u>)	16 - 25	E
(c) Θ (angle of propagation direction p from y axis in <u>degrees</u>)	31 - 40	E
(d) \$\overline{p}\$ (angle of projection of propagation direction on the x,z plane from z axis in degrees)	46 - 55	E
Card Group #2 (total = unlimited)		

(a)	Frequency	of	incident	wave	in	<u>Hertz</u>	1 - 10	E
-----	-----------	----	----------	------	----	--------------	--------	---

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x=0,y=0,z=0, is fixed by the user according to the specification on Card Group I. (See Figure 5-1 and 5-2.) The zero phase of the incident wave is taken at the origin of this coordinate system. usse is the distribution of the structure of the state of the structure of the state of the structure of the

Card Group #2 for FSO=1 consists of an unlimited number of cards with each frequency of the incident wave on each card. More than one frequency card may be included in this frequency card group. The program will process the data provided by Groups I and II and the wave orientation data in Group #1 in Table 3 and compute the response at the frequency on the first frequency card. It will then recompute the response at each frequency on the remaining frequency cards. The program assumes that the data on card Groups I and II and the wave orientation data in Group #1 in Table 3 are to be used for all the remaining frequencies. If this is not intended by the user, then one may only run the program for one frequency at a time. This feature, however, can be quite useful. If the termination networks are purely resistive, i.e., frequency independent, then one may use as many frequency cards as desired in Group #2 and the program will compute the response of the line at each frequency without the necessity for the user to input the data in Groups I and II and the wave orientation data for each additional frequency. Many of the time-consuming calculations which are independent of frequency need to be computed only once so that this mode of useage will save considerable computation time when the response at many frequencies is desired. If, however, the termination network characteristics (in Group II) are complex-valued (which implies frequency dependent), one must run the program for only one frequency at a time.

5.3.2 Nonuniform Field Illumination, FSO=2

The format of the Field Specification Cards, Group III, for nonuniform

field illumination, FSO=2, is shown in Table 4. The first card group, Group #1, consists of one and only one card which contains the frequency of the field.

The remaining cards contain the values of the longitudinal electric field (magnitude and phase) along the n wires (and reference wire for TYPE 1 structures) which are directed in the +x direction, and the transverse electric field along straight line contours joining the i-th wire and the reference conductor at x=0 and x= λ . The directions of the transverse field at these specification points are tangent to the contours and directed from the reference conductor to the i-th wire. For TYPE 1 structures, the precise location and orientation of the transverse field specification contours should be clear. For TYPE 2 structures, the transverse field specification contours should comprise the shortest path in the y, z plane between the ground plane and the i-th wire, i.e., it should be perpendicular to the transverse field specification contours should comprise the shortest path in the y, z plane between the interior wall of the cylindrical shield and the i-th wire. (See Figure 5-5.)

The ordering of the card Groups #2-#9 is quite logical but somewhat involved to describe. The philosophy of the ordering is as follows. If TYPE 1 structures are selected, we first describe the longitudinal electric field (magnitude and phase) along the reference wire at (N₁₀+1) specification points. This is done in Groups #2 and #3. (If TYPE = 2 or 3, Groups #2and #3 are omitted and it is assumed that the net incident electric field is obtained, i.e., the electric field tangent to the ground plane (TYPE=2) and the interior of the cylindrical shield (TYPE=3) is zero.) In Group #2,

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we communicate the number N_{LO} and the magnitude and phase of the field at the first specification point at x=0. In Group #3, we compute the locations of the remaining N_{LO} specification points and the magnitude and phase of the field at each of these specification points. The cards in this group must be arranged sequentially so that each specification point is located to the right of the previous point. In addition, the last (N_{LO}^{+1}) specification point must be equal to the line length, \mathbf{I} , i.e., located at x= \mathbf{I} .

The remaining card groups (#4-#9) use the same philosophy as Group #2 and #3 and describe, for each wire from 1 to n, the quantities (in this order): 「日本語言なないない」とないである」となったので、「ないないない」となって、ないていたいとなった。

(1) longitudinal field on i-th wire,

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- (2) transverse field at x=0 between the reference conductor and i-th wire, and
- (3) transverse field at x=I between the reference conductor and i-th wire.

For example, after Group #3 we must have Groups #4-#9 for wire 1, Groups #4=#9 for wire 2, ---, Groups #4-#9 for wire n. This is illustrated in Figure 5-6.

It should be noted that the incident electric field which one specifies in Card Groups #2-#9 is the incident field with the n wires (and the reference wire for TYPE 1 structures) removed. This is inherent in the derivations of Chapter II. Thus one specifies the longitudinal electric field at points along the positions of each wire.

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Group #1 Group #2 Group #3 Group #4 ... Group #9 Group #9 Group #4 ... Group #9 for wire #1 for wire #2 Group #9 for wire #n Group #9

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Figure 5-6. Ordering of Card Groups in Group III for FSO = 2.

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Form	at of the Field Specification Cards, Grou	p III, for Nonuni	form Fields,
	FSO = 2 (see Figure 5-	5)	
Card	Group #1 (total = 1):	card column	format
(a)	Frequency of incident field in Hertz	1 - 10	E
Card	Group #2 (total = 1 if TYPE = 1 absent if TYPE = 2 or 3)		
(a)	N_{20} (number of field specification points along reference wire = N_{20}^{+1}	1 - 10	I
(b)	<pre> E₁₀ (magnitude of electric field along reference wire in +x direction at x=0 in volts/meter)</pre>	21 - 30	Е
(c)	$\frac{E_{2,0}^{(0)}}{E_{2,0}}$ (phase of electric field along reference wire at x=0 in <u>degrees</u>)	41 - 50	E
Card	Group #3 (total = N ₂₀ if TYPE=1 absent if TYPE = 2 or 3)		
(a)	<pre>x(m) (e)eccric field specification point along reference wire in meters)</pre>	1 - 10	E
(b)	(m) E ₁₀ (megnitude of electric field at $x_{(0)}$ in $+x$ direction in <u>volts/meter</u>)	21 - 30	E
(c)	$\frac{\binom{(m)}{E_{l0}}}{\underset{l0}{\text{ x}_{l0}^{(m)}}} \text{ in degrees})$	41 - 50	E

TABLE 4 (continued)

Note: $m = 1, 2, ---, N_{20}$ and $x_{20}^{(N_{20})}$ (the last specification point) must equal the line length, \mathbf{I} . The cluss in Group #3 must be arranged such that $x_{20}^{(m)} \leq x_{20}^{(m+1)}$

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			TABLE 4 (conti	lnued)	
Card	Group	#4 (total = 1)		card column	format
(a)	N _{li} (number of field s points along i-th N _{li} +1)	pecification wire =	1 - 10	Ĩ
(b)	E ⁽⁰)	(magnitude of el in +x direction wire at x=0 in	ectric field along i-th volts/meter)	21 - 30	E
(c)	$\left/ E_{li}^{(0)} \right $	(phase of electr i-th wire at x=	ic field along 0 in <u>degrees</u>)	41 - 50	E
Card	Group	#5 (total = N _{li})	-		
(a)	x ^(m) Li	(electric field s point along i-th meters)	pecification wire in	1 - 10	. E
(b)	E ^(m) Li	(magnitude of el at x ^(m) in +x d <u>volta/meter</u>)	ectric field iirection in	21 - 30	Е
(c)	$\frac{E_{li}^{(m)}}{E_{li}}$	(phase of electr x(m) in <u>degrees</u>	ric field at 3)	41 - 50	E
Note	; m =	1,2,,N ₂₁ and	(N _{li}) x _{li} (the las	st specification poin	it) must
equa	1 the	line length, I.	The cards in G	roup #5 must be arran	iged such
that					

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 $x_{li}^{(m)} < x_{li}^{(m+1)}$

Card Group #6 (total = 1)

(a)	N _{tOi} (number of field specification points at x=0 on straight line contour between reference con- ductor and i-th wire = N _{tOi} +1)	1 - 10	I
(b)	$ E_{t01}^{(0)} $ (magnitude of electric field) 21 - 30	a

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TABLE 4 (continued Card Group #6 (total = 1) continued	d) card column	format
(c) $\frac{E_{t0i}^{(0)}}{E_{t0i}}$ (phase of electric field on contour at x=0 in <u>degrees</u>)	41 - 50	E
Card Group #7 (total = N _{tOi})		
 (m) (electric field specification point on contour between reference conductor and i-th wire at x=0 in meters) 	1 - 10	E
(b) E ^(m) _{t0i} (magnitude of electric field on contour at x=0 at ρ ^(m) in volts/meter)	21 - 30	E
(c) $\frac{E_{t01}^{(m)}}{E_{t01}}$ (phase of electric field on contour at $\rho_{t01}^{(m)}$ in <u>degrees</u>)	41 - 50	E
<u>Note</u> : $m = 1, 2,, N_{tOi}$ and $\rho_{tOi}^{(N_{tOi})}$ (the last s	pecification point)	must be
located at the center of the i-th wire at $x=0$.	. The cards in Grou	ip #7 must
be arranged such that		

$$\rho_{t0i}^{(m)} < \rho_{t0i}^{(m+1)}$$

Card Group #8 (total = 1)

(a) N_t (number of field specification 1-10 I points on straight line contour at x=Z between reference conductor and i-th wire = N_t + 1)
 (0)

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- (b) $|E_{txi}^{(0)}|$ (magnitude of electric field 21 30 on contour at x= \neq in <u>volts/meter</u>)
- (c) $\frac{E_{tI1}^{(0)}}{at x=1}$ (phase of electric field on contour 41 50 at x=1 in <u>degrees</u>)



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Card	Group	#9 (total = N _t ti)	TABLE 4 (continued) <u>card column</u>	format
(a)	ρ <mark>(m)</mark> (t ≭i (electric field spe on contour between ductor and i-th wi	cification point reference con- re at x=% in <u>meters</u>)	1 - 10	E
(b)	E ^(m) t≠1	(magnitude of ele contour at x=≭a volts/meter)	ctric field on t $\rho(\mathbf{m})$ in txi	21 - 30	E
(c)	$\frac{E_{tli}^{(m)}}{E_{tli}}$	(phase of electric at x= X at ρ(m) in tXi	c field on contour n <u>degrees</u>)	41 - 50	E
Note	: m=1,2	,, N_{tzi} and ρ_{tzi}	(the last specif	ication point) mus	t be
loca	ted at	the center of the	i-th wire at $x=Z$.	The cards in Group	#9
must	be arr	anged such that	,		

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Note: Card Groups #4 - 9 must be repeated for wires 1 to n and arranged sequentially for wire 1, wire 2, ---, wire n.

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VI. EXAMPLES OF PROGRAM USAGE

Several examples of program usage will be described in this Chapter. These examples will serve to illustrate preparation of the data input cards as well as provide partial checks on the proper functioning of the program. The data input cards as well as the computed results will be shown for each example.

6.1 Example I

In this Chapter we will show an example of a two wire line above a ground plane (TYPE=2) illuminated by a uniform plane wave (FSO=1). The solution for the terminal currents for a l volt/meter field with several angles of incidence will be shown. The image problem will also be considered by replacing the ground plane with the images of the wires resulting in a four wire line (N=3,TYPE=1). The corresponding currents in the wires for the problem of two wires above a ground plane should be twice those for the image problem.

6.1.1 Two Wires Above a Ground Plane

The problem considered here is shown in Figure 6-1. Wire #1 has a radius of 30 mils and is 5 cm above the ground plane. Wire #2 has a radius of 10 mils and is 2 cm above the ground plane. The two wires are separated horizontally by 4 cm. The cross-section of wire #1 is located at y=5 cm, z=0. The cross-section of wire #2 is located at y=2 cm, z=4 cm. The line length is 5m and μ_r =1, ε_r =1 (a logical choice although any ε_r and μ_r may be used in the program). Each wire is terminated with a single impedance (in this case purely resistive) between the wire and the ground plane. Clearly one may chose the load structure option of LSO=11 with the

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Figure 6-1. Example I.

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terminal impedance matrices

$$Z_{0} = \begin{bmatrix} 100 & 0 \\ 0 & 500 \end{bmatrix} \qquad Z_{n} = \begin{bmatrix} 500 & 0 \\ 0 & 1000 \end{bmatrix}$$

Three orientations of the incident field will be considered:

(a)
$$E_{m} = 1 \text{ V/m}, \Theta_{E} = 30^{\circ}, \Theta_{p} = 150^{\circ}, \phi_{p} = 40^{\circ}$$

(b) $E_{m} = 1 \text{ V/m}, \Theta_{E} = 0^{\circ}, \Theta_{p} = 90^{\circ}, \phi_{p} = 90^{\circ}$
(c) $E_{m} = 1 \text{ V/m}, \Theta_{E} = 0^{\circ}, \Theta_{p} = 180^{\circ}, \phi_{p} = 90^{\circ}$

Notice that case (b) has the wave propagating in the +x direction along the line axis with \vec{E} in the +y direction, i.e.,

$$\vec{E} = e^{-jkx} \vec{y}$$

Case (c) has the wave propagating broadside to the line (in the -y direction) with \vec{E} in the +x direction, i.e.,

$$\vec{E} = e^{jky} \vec{x}$$

Four frequencies of excitation will be investigated:

1 MHz, 10 MHz, 100 MHz, 1GHz (1E6), (1E7), (1E8), (1E9)

and since the loads are resistive, the frequency iteration feature of the program can be used by simply placing all four frequency cards as a group at the end of the program.

The reason for using these frequencies is that for 1 MHz, the crosssectional dimensions of the line are electrically small. For 1 GHz, they are not. This will serve to further illustrate why we require that the crosssectional dimensions of the line be electrically small. To illustrate this let us arbitrarily select the distance between wire #1 and the image of wire #1 to be the "largest" cross-sectional dimension of the line. This distance

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is given Ly

 $d_{max} = 10 \text{ cm}$

The quantities kd_{max} (in degrees) at the above four frequencies are:

frequency	kd (degrees)	$\frac{d_{max}}{\lambda}$	
1 E6	.12	.000334	
1 E7	1.2	.003336	
1 E8	12.0	.033356	
1 E9	120.0	.333564	

Notice that for the frequency of 1 E9, the cross-sectional dimensions of the line are certainly not electrically small. For the other frequencies, they probably are.

The input data cards for the angles of incidence in (a), (b) and (c) are shown in Figure 6-2(a), (b) and (c), respectively. The results are shown in Figure 6-3.

6.1.2 Two Wires Above a Ground Plane by the Method of Images

Here we solve the problem considered in the previous section by the method of images. The image problem becomes a four wire problem (N=3, TYPE=1) as shown in Figure 6-4. Here we choose (arbitrarily) the image wire of wire #1 in the previous problem as the reference wire. The various wire radii, and coordinates are:

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Figure 6-2(a). Data cards for the problem in Figure 6-1 with $E_m = 1V/m$, $\Theta_E = 30^\circ$, $\Theta_p = 150^\circ$, $\phi_p = 40^\circ$.

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1 2 3 4 3 4 ¹ 4 5 4 11 4 13 4 15 4 17 4 11 70 77 72 72	33 34 34 34 34 34 44 44 44 44 44 44 36 34 35 35 36 36 36 36 36 36 36 36 36 37 37 38 38 38 39 39 38 38 38 38 38 38 38 38 38 38 38 38 38
	29.29.29.29.29.49.44.44.44.44.44.49.22.23.23.23.23.24.44.44.45.45.44.44.44.44.44.44.44.44.44
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500.E0 0.E0	
	ананнананалалаланананыный ананыныныныныныныныныныныныныныныныныны
10.E0 6.E-2	аналы, аларынанананананананананананананананананан
30.E0 0.E0	យកកត់បកកត់តិតិតិតិតិតិតាល់កំណុងកំណុងកំណុងកំណុងតំណាត់តាល់តាត់តាត់តាត់តាក់តាក់តាក់តាក់តាក់តាក់
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Figure 6-2(b). Data cards for the problem in Figure 6-1 with $E_m = 1 \text{ V/m}$, $\Theta_E = 0$, $\Theta_p = 90$, $\phi_p = 90$.

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	******	*******
1 2 3 4 3 6 7 8 5 6 11 8 8 1 8 8 1 8 8 8 8 8 8 8 8 8 8 8 8 8 8	1252231232232352353535353535353555555555	****

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123456788448184818481848181818222222222	********	

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Figure 6-2(c). Data cards for the problem in Figure 6-1. with $E_m = 1 V/m$, $\Theta_E = 0^\circ$, $\Theta_p = 180^\circ$, $\phi_p = 90^\circ$.

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(a)
$$E_m = 1 V/m, \Theta_E = 30, \Theta_p = 150, \phi_p = 40$$

f = 1 MHz

$$I_1(0) = 3.298E-6 / 89.41$$
 $I_1(x) = 2.837E-7 / 86.22$
 $I_2(0) = 7.336E-7 / 88.68$ $I_2(x) = 1.782E-7 / -91.58$

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f = 10 MHz

$$I_1(0) = 3.315E-5 / 84.07$$
 $I_1(z) = 3.116E-6 / 53.64$
 $I_2(0) = 7.191E-6 / 76.96$ $I_2(z) = 1.732E-6 / -105.55$

$$\frac{f = 100 \text{ MHz}}{I_1(0) = 2.495E-4 / -1.650} I_1(x) = 1.024E-4 / -142.78}$$
$$I_2(0) = 3.450E-5 / 4.802 I_2(x) = 1.101E-5 / -177.51$$

$$\frac{f = 1 \text{ GHz}}{I_1(0) = 2.089E-4 \ 2.521 \ I_1(x) = 9.315E-5 \ -139.76}$$
$$I_2(0) = 3.317E-5 \ -10.474 \ I_2(x) = 1.089E-5 \ 172.48$$

Figure 6-3. The problem in Figure 6-1.

-119-

(b)
$$E_m = 1 V/m, \Theta_E = 0, \Theta_p = 90, \phi_p = 90$$

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Provide and the second second

$$I_{1}(0) = 9.294E-6 \frac{89.09}{1}$$

$$I_{1}(x) = 2.333E-6 \frac{87.87}{1}$$

$$I_{2}(0) = 1.963E-6 \frac{88.44}{1}$$

$$I_{2}(x) = 1.432E-7 \frac{-93.46}{1}$$

$$\frac{f = 10 \text{ MHz}}{I_1(0) = 9.316E-5 / 80.85} \qquad I_1(z) = 2.336E-5 / 68.63$$
$$I_2(0) = 1.920E-5 / 74.56 \qquad I_2(z) = 1.383E-6 / -124.51$$

$$\frac{f = 100 \text{ MHz}}{I_1(0) = 4.638E - 4 - 37.08} \qquad I_1(z) = 1.150E - 4 - 156.86$$
$$I_2(0) = 6.602E - 5 - 24.28 \qquad I_2(z) = 3.021E - 6 - 70.15$$

$$f = 1 GHz$$

$$I_{1}(0) = 4.587E - 4 - 37.91$$

$$I_{1}(2) = 1.138E - 4 - 158.43$$

$$I_{2}(0) = 6.567E - 5 - 24.92$$

$$I_{2}(2) = 3.054E - 6 - 68.47$$

Figure 6-3. The problem in Figure 6-1.

-120-

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(c)
$$E_{m} = 1 V/m, \Theta_{E} = 0, \Theta_{p} = 180, \phi_{p} = 90$$

f = 1 MHz

$$I_{1}(0) = 3.494E-6 / 90.08 \qquad I_{1}(x) = 3.493E-6 / 89.27$$

$$I_{2}(0) = 5.590E-7 / 89.95 \qquad I_{2}(x) = 5.589E-7 / 89.44$$

$$f = 10 MHz$$

$$I_1(0) = 3.553E-5 / 90.71$$

 $I_1(2) = 3.500E-5 / 82.65$
 $I_2(0) = 5.656E-6 / 89.41$
 $I_2(2) = 5.581E-6 / 84.45$

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$$f = 100 \text{ MHz}$$

いたが、ショントの方法で

$$I_{1}(0) = 5.316E-4 / 33.83 \qquad I_{1}(z) = 1.988E-4 / -6.817$$

$$I_{2}(0) = 8.392E-5 / 52.80 \qquad I_{2}(z) = 4.634E-5 / 35.77$$

$$\frac{f = 1 \text{ GHz}}{I_1(0) = 4.402E-4 / 33.09} \qquad I_1(2) = 1.632E-4 / -7.429}$$
$$I_2(0) = 8.585E-5 / 52.98 \qquad I_2(2) = 4.664E-5 / 37.48$$

Figure 6-3. The problem in Figure 6-1.

-121-



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Wire	Radius	<u>z</u> i	<u>y</u> <u>1</u>
0	30 mils	0	0
1	30 mils	0	10 cm
2	10 mils	4 cm	7 cm
3	10 mils	4 cm	3 cm

The four frequencies of excitation for the ground plane problem in the previous section (1MHz, 10MHz, 100MHz, 1GHz) as well as the three orientations of the plane wave will be considered here. Note here that the zero phase reference for the plane wave is not the same as for the ground plane problem. Here the zero phase reference is displaced downward (in the -y direction) from the zero phase reference for the ground plane problem in the previous section by 5 cm. This means that the phase angles of the currents in this problem will differ from the phase angles of the corresponding currents in the ground plane example by k(5 cm) degrees or

fre	equency	<u>k(5</u>	cm)	(degrees)
1	MHz		•(600
10	MHz			5004
L00	MHz		6.(0042
1	GHz		60.0)415

The next problem remaining is to determine the appropriate representation of the terminal networks. This type of situation was considered in Section 2.6 of Chapter II. From Figure 6-4 we may write (note that the line voltages are with respect to the reference wire here)

-123-

$$I_{1}(0) = -(1/200) V_{1}(0)$$

$$I_{2}(0) = (1/1K) (V_{3}(0) - V_{1}(0))$$

$$I_{3}(0) = (1/1K) (V_{2}(0) - V_{3}(0))$$

 $I_{1}(\vec{x}) = (1/1K) V_{1}(\vec{x})$ $I_{2}(\vec{x}) = (1/2K) (V_{2}(\vec{x}) - V_{3}(\vec{x}))$ $I_{3}(\vec{x}) = (1/2K) (V_{3}(\vec{x}) - V_{2}(\vec{x}))$

Thus we select the load structure option LSO = 22 and the terminal admittance matrices become

$$\mathbf{x}_{0} = \begin{bmatrix} 5E-3 & 0 & 0\\ 0 & 1E-3 & -1E-3\\ 0 & -1E-3 & 1E-3 \end{bmatrix} \qquad \mathbf{y}_{-1} = \begin{bmatrix} 1E-3 & 0 & 0\\ 0 & 5E-4 & -5E-4\\ 0 & -5E-4 & 5E-4 \end{bmatrix}$$

The input data cards are shown in Figure 6-5. The results are shown in Figure 6-6.

Note that for all angles of incidence the magnitudes of $I_2(0)$ and $I_3(0)$ for each frequency are equal as are the magnitudes of $I_2(\mathbf{X})$ and $I_3(\mathbf{X})$. Further note that $I_2(0)$ and $I_3(0)$ are precisely 180° out of phase as are $I_2(\mathbf{X})$ and $I_3(\mathbf{X})$. Therefore we have

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$$I_2(0) + I_3(0) = 0$$

 $I_2(z) + I_3(z) = 0$

for all frequencies as they should be.

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Figure 6-5(a). Data cards for the problem in Figure 6-4 with $E_m = 1 \text{ V/m}$, $\Theta_E = 30^\circ$, $\Theta_p = 150^\circ$, $\phi_p = 40^\circ$.

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Figure 6-5(b). Data cards for the problem in Figure 6-4 with $E_m = 1 \text{ V/m}$, $\Theta_E = 0^\circ$, $\Theta_p = 90^\circ$, $\phi_p = 90^\circ$.

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Figure 6-5(c). Data cards for the problem ip Figure 6-4 with $E_m = 1 \text{ V/m}$, $\Theta_E = 0$, $\Theta_p = 180$, $\phi_p = 90$.

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(a)
$$E_m = 1 \text{ V/m}, \Theta_E = 30, \Theta_p = 150, \phi_p = 40$$

f = 1 MHz

$$I_{1}(0) = 1.649E-6 89.46 I_{1}(z) = 1.419E-7 86.28$$

$$I_{2}(0) = 3.668E-7 88.79 I_{2}(z) = 8.912E-8 -91.43$$

$$I_{3}(0) = 3.668E-7 -91.21 I_{3}(z) = 8.912E-8 88.57$$

$$f = 10 MHz$$

$$I_{1}(0) = 1.658E-5 \ 84.57 \qquad I_{1}(z) = 1.558E-6 \ 54.19 \\ I_{2}(0) = 3.597E-6 \ 78.11 \qquad I_{2}(z) = 8.661E-7 \ -104.07 \\ I_{3}(0) = 3.597E-6 \ -101.89 \qquad I_{3}(z) = 8.661E-7 \ 75.93 \\ \ \end{array}$$

f = 100 MHz

$$I_{1}(0) = 1.247E-4 \ \underline{3.519} \qquad I_{1}(z) = 5.118E-5 \ \underline{-137.55} \\ I_{2}(0) = 1.763E-5 \ \underline{15.05} \qquad I_{2}(z) = 5.657E-6 \ \underline{-165.87} \\ I_{3}(0) = 1.76eE-5 \ \underline{-164.95} \qquad I_{3}(z) = 5.657E-6 \ \underline{14.13} \\ \end{bmatrix}$$

f = 1 GHz

And an and a second

$$I_{1}(0) = 1.037E-4 / 55.36 \qquad I_{1}(z) = 4.631E-5 / -87.41$$

$$I_{2}(0) = 2.591E-5 / 74.23 \qquad I_{2}(z) = 1.024E-5 / -93.50$$

$$I_{3}(0) = 2.591E-5 / -105.77 \qquad I_{3}(z) = 1.024E-5 / 86.50$$

Figure 6-6. The problem in Figure 6-4.

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(b)
$$E_m = 1 V/m, \Theta_E = 0, \Theta_p = 90, \phi_p = 90$$

f = 1 MHz

$$I_{1}(0) = 4.647E-6 \boxed{89.09} \qquad I_{1}(\textbf{X}) = 1.166E-6 \boxed{87.87}$$

$$I_{2}(0) = 9.813E-7 \boxed{88.44} \qquad I_{2}(\textbf{X}) = 7.158E-8 \boxed{-93.46}$$

$$I_{3}(0) = 9.813E-7 \boxed{-91.56} \qquad I_{3}(\textbf{X}) = 7.158E-8 \boxed{86.54}$$

ź

$$f = 10 MHz$$

$$I_{1}(0) = 4.658E-5 / 80.85 \qquad I_{1}(z) = 1.168E-5 / 68.63$$

$$I_{2}(0) = 9.599E-6 / 74.56 \qquad I_{2}(z) = 6.913E-7 / -124.51$$

$$I_{3}(0) = 9.599E-6 / -105.44 \qquad I_{3}(z) = 6.913E-7 / 55.49$$

$$f = 100 \text{ MHz}$$

$$I_{1}(0) = 2.319E-4/-37.08$$

$$I_{1}(z) = 5.751E-5/-156.86$$

$$I_{2}(0) = 3.301E-5/-24.28$$

$$I_{2}(z) = 1.510E-6/-70.15$$

$$I_{3}(z) = 3.301E-5/155.72$$

$$I_{3}(z) = 1.510E-6/-109.85$$

$$t = 1 GHz$$

$$I_{1}(0) = 2.294E-4/-37.91 \qquad I_{1}(z) = 5.689E-5/-158.43$$

$$I_{2}(0) = 3.284E-5/-24.92 \qquad I_{2}(z) = 1.527E-6/-68.47$$

$$I_{3}(0) = 3.284E-5/155.08 \qquad I_{3}(z) = 1.527E-6/-111.53$$

Figure 6-6. The problem in Figure 6-4.

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(c)
$$E_{m} = 1 V/m$$
, $\Theta_{E} = 0$, $\Theta_{p} = 180$, $\phi_{p} = 90$

$$\frac{f = 1 \text{ MHz}}{I_1(0) = 1.747E-6 / 90.14}$$

$$I_1(z) = 1.747E-6 / 89.33$$

$$I_2(0) = 2.795E-7 / 90.01$$

$$I_2(z) = 2.794E-7 / 89.50$$

$$I_3(z) = 2.794E-7 / -90.50$$

$$f = 10 MHz$$

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$$I_{1}(0) = 1.776E-5 / 91.31 \qquad I_{1}(z) = 1.750E-5 / 83.25$$

$$I_{2}(0) = 2.828E-6 / 90.01 \qquad I_{2}(z) = 2.791E-6 / 85.05$$

$$I_{3}(0) = 2.828E-6 / -89.99 \qquad I_{3}(z) = 2.791E-6 / -94.95$$

f = 100 MHz

$$I_{1}(0) = 2.658E-4 / 39.83 \qquad I_{1}(z) = 9.938E-5 / -81.27$$

$$I_{2}(0) = 4.196E-5 / 58.80 \qquad I_{2}(z) = 2.317E-5 / 41.78$$

$$I_{3}(0) = 4.196E-5 / -121.20 \qquad I_{3}(z) = 2.317E-5 / -138.22$$

f = 1 GHz

$$I_{1}(0) = 2.201E-4 / 93.14 \qquad I_{1}(z) = 8.161E-5 / 52.61$$

$$I_{2}(0) = 4.293E-5 / 113.03 \qquad I_{2}(z) = 2.332E-5 / 97.52$$

$$I_{3}(0) = 4.293E-5 / -66.97 \qquad I_{3}(z) = 2.332E-5 / -82.48$$

Figure 6-6. The problem in Figure 6-4,

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6.1.3 Comparison of the Two Solutions

The terminal currents (I_1, I_2) in Figure 6-1 (the ground plane problem) should be exactly twice the magnitude of the corresponding currents (I_1, I_2) in Figure 6-4 (the image problem). For the case of propagation in the +x direction with \vec{E} in the +y direction:

(b)
$$\Theta_{E} = 0, \Theta_{p} = 90, \phi_{p} = 90$$

 $\overrightarrow{E} = e^{-jkx} \overrightarrow{v}$

and the case of propagation in the -y direction with \vec{E} in the +x direction:

(c)
$$\Theta_{E} = 0$$
, $\Theta_{p} = 180$, $\phi_{p} = 90$
 $\overrightarrow{E} = e^{jky} \overrightarrow{x}$

this is precisely the case for all frequencies. (Although not shown here, the results were printed out to 16 digits and agreed to 15 digits.)

However, consider the case of

(a)
$$\Theta_{\rm E} = 30, \Theta_{\rm p} = 150, \phi_{\rm p} = 40$$

Note that the corresponding currents for the ground plane problem in Figure 6-1 are precisely twice those for the image problem in Figure 6-4 for 1 MHz and 10 MHz. For 100 MHz, $I_1(0)$ and $I_1(z)$ correspond exactly and $I_2(0)$ and $I_2(z)$ correspond very closely. However, for 1 GHz, only currents $I_1(0)$ and $I_1(z)$ correspond whereas $I_2(0)$ and $I_2(z)$, although within a factor of two, do not correspond. The reason for this becomes clear when we consider the definition of line voltages used for the two problems. Consider Figure 6-7. We have shown the cross-section of particular wire above a ground plane in Figure 6-7(a), the wire voltage, V, is shown and the potential difference between the wire and its image is 2V. In Figure 6-7(b), we have shown the corresponding image problem and the voltage of each wire is defined with respect to the reference wire, i.e., V_1 and V_2 . For the two representations to yield corresponding results, one would expect that

$$2v \stackrel{?}{=} (v_1 - v_2)$$

These voltages are related to the integral of $\vec{E}^{(inc)}$ in the transverse (y,z) plane along the contours shown in Figure 6-7 and are included in the vectors $\vec{E}_t^{(inc)}(0)$ and $\vec{E}_t^{(inc)}(\vec{z})$. Clearly these will correspond only if $\vec{E}^{(inc)}$ is curl free in the transverse (y,z) plane, i.e., only if there is no component of $\vec{H}^{(inc)}$ in the x direction which penetrates a transverse contour. For angles of incidence $\theta_E = 0$, $\theta_p = 90$, $\phi_p = 90$ and $\theta_E = 0$, $\theta_p = 1.80$, $\phi_p = 90$, this is clearly the case and the results show this. However, for $\theta_E = 30$, $\theta_p = 150$, $\phi_p = 40$, there is a component of $\vec{H}^{(inc)}$ in the x direction. However, for f = 1MHz, 10 MHz 100 MHz, the cross-sectional dimensions of the line are electrically small and the fact that $\vec{E}^{(inc)}$ is not curl free in the y,z plane does not matter. For 1 GHz, the cross-sectional dimensions of the line are not electrically small and it does matter as is evidenced in the computed results.

6.2 Example II

In this Section we will consider a problem which was investigated by Harrison using an alternate formulation [5,8]. The problem consists of three wires in free space all of radius 10^{-3} m which lie in the x,y plane with adjacent wire separations of 10^{-2} m as shown in Figure 6-8. The line is 10 m

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Figure 6-8. Example II.

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long and various loads connect each wire to a central point.

The termination impedances are

$$z_{01} = 50 - j 25$$
 $z_{02} = 100 + j 100$ $z_{03} = 25 + j 25$
 $z_{21} = 50 + j 25$ $z_{22} = 100 - j 50$ $z_{23} = 150 - j 50$

Obviously we should select LSO = 12 and the termination impedance matrices become

$$Z_{0} = \begin{bmatrix} (Z_{01} + Z_{03}) & Z_{03} \\ Z_{03} & (Z_{02} + Z_{03}) \end{bmatrix} = \begin{bmatrix} 75 + j0 & 25 + j & 25 \\ 25 + j & 25 & 125 + j & 125 \end{bmatrix}$$

$$Z_{\chi} = \begin{bmatrix} (Z_{\chi 1} + Z_{\chi 3}) & Z_{\chi 3} \\ Z_{\chi 3} & (Z_{\chi 2} + Z_{\chi 3}) \end{bmatrix} \begin{bmatrix} 200 - j \ 25 & 150 - j \ 50 \\ 150 - j \ 50 & 250 - j \ 100 \end{bmatrix}$$

AlV/m uniform plane wave is propagating in the +y direction with \vec{E} in the +x direction, i.e., $\vec{E}^{(inc)} = e^{-jky} \vec{x}$. Therefore $E_m = 1$, $\theta_E = 180$, $\theta_p = 0$, $\phi_p = 9$?. Harrison showed the result for the terminal currents computed by his method for $k \not{x} = 1.5$. The line is 10 m long. Therefore the frequency is 7157018.74 Hz. The input data cards are shown in Figure 6-9. The computed results are shown in Figure 6-10 and compared with those obtained by Harrison. Note that the results computed by this method agree with those computed by Harrison to within three digits. The main reason that the results do not agree precisely is that the ratio of line length to wavelength at this frequency is .239. Thus we are entering a frequency range where the variation of line responses with frequency is generally quite rapid

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> Figure 6-9. Data cards for the problem in Figure 6-8 with $E_m = 1 V/m$, $\Theta_E = 180^\circ$, $\Theta_p = 0^\circ$, $\phi_p = 90^\circ$, FSO=1.

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$$E_{m} = 1 \text{ V/m}, \Theta_{E} = 180, \Theta_{p} = 0, \phi_{p} = 90$$

<u>f = 7357018.74 Hz (k2 = 1.5)</u>

Computed with WIRE:

$$I_{1}(0) = 1.066E-5 / -99.83 \qquad I_{1}(z) = 1.221E-5 / 158.65$$
$$I_{2}(0) = 5.647E-5 / -159.07 \qquad I_{2}(z) = 2.784E-5 / -148.26$$

Computed by Harrison:

$$|I_1(0)| = 1.065E-5$$
 $|I_1(2)| = 1.220E-5$
 $|I_2(0)| = 5.644E-5$ $|I_2(2)| = 2.784E-5$

Figure 6-10. The problem in Figure 6-8 with FSO = 1.

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and any seemingly insignificant approximations in the input data $(k \not z \ z \ 1.5)$ can cause significant changes in the result. In fact the program was internally modified (temporarily) such that $k \not z$ was precisely 1.5 and the results agreed exactly.

One additional case will be computed in which $E_m = 1$, $\theta_E = 0$, $\theta_p = 90$, $\phi_p = 90$, i.e., the wave is propagating in the +x direction with \vec{E} in the plane of the wires, i.e., the +y direction,

$$\dot{E}^{(inc)} = e^{-jkx} \dot{y}$$

The input data cards are shown (for $k \chi = 1.5$) in Figure 6-11 and the computed results are shown in Figure 6-12.

6.2.1 Use of the Monuniform Field Specification Option, FSO = 2

In this Section we will solve the two problems considered in the previous Section by using the nonuniform field specification option.

For the first example we consider the problem in Figure 6-8 with $E_m = 1 \text{ V/m}, \Theta_E = 180, \Theta_p = 0, \phi_p = 90$. To use the nonuniform field specification option, we must describe the magnitude and phase of the incident electric field along the three wires and along straight line contours (the y axis in this case) between each of the two wires and the reference wire at x = 0 and x = X. Because of this particular field orientation, the specification of these quantities is quite simple. Clearly, the transverse fields are zero. The longitudinal field at all points along the reference wire are 1/0; along wire 1 are $1/k \times 10^{-2} = 1/(-8.5944E-2)$ and along wire 2 are $1/k \times 2 \times 10^{-2} = 1/(-1.7189E-1)$. Although redundant, 11 specification points for the longitudinal fields and 6 specification points for the transverse fields will be used. The data cards are shown in Figure

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Figure 6-11. Data cards for the problem in Figure 6-8 with $E_m = 1 V/m$, $\Theta_E = 0^\circ$, $\Theta_p = 90^\circ$, $\phi_p = 90^\circ$, FSO=1.

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$E_{m} = 1 V/m, \Theta_{E} = 0, \Theta_{P} = 90, \phi_{P} = 90$

$$f = 7157018.74 \text{ Hz} (\text{k} \neq 1.5)$$

Sector of the

$$I_{1}(0) = 1.216E-5 / 17.18 \qquad I_{1}(x) = 1.572E-5 / -49.19$$

$$I_{2}(0) = 6.708E-5 / -13.76 \qquad I_{2}(x) = 2.849E-5 / -129.84$$

Figure 6-12. The problem of Figure 6-5 with FSO = 1.

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6-13 and the computed results are shown in Figure 6-14. These results compare (and should compare): cxactly to those in Figure 6-10 where the uniform plane wave option was used.

The next problem is to use the field orientation of $\theta_E = 0$, $\theta_p = 90$, $\phi_p = 90$. In this case, the longitudinal fields along all wires will be zero whereas the transverse fields at all points along the contours at x = 0will be 1/0 whereas those of x = 7 will be 1/kT = 1/(-85.943669). The data cards are shown in Figure 6-15 and the computed results are shown in Figure 6-16. These results compare (and should compare) exactly to those in Figure 6-12 where the uniform plane wave option was used.

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Figure 6-13. Data cards for the problem in Figure 6-8 with $E_m = 1 \text{ V/m}$, $\Theta_p = 180^\circ$, $\Theta_p = 0^\circ$, $\phi_p = 90^\circ$, FSO=2 (continued).

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Figure 6-13. Data cards for the problem in Figure 6-8 with $E_m = 1 \text{ V/m}$, $\Theta_E = 180^\circ$, $\Theta_p = 0^\circ$, $\phi_p = 90^\circ$, FSO=2 (cont.)

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f = 7157018.74 Hz (k \neq 1.5)

$$I_{1}(0) = 1.066E-5 / -99.83 \qquad I_{1}(2) = 1.221E-5 / 158.65$$
$$I_{2}(0) = 5.647E-5 / -159.07 \qquad I_{2}(2) = 2.784E-5 / -148.26$$

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Figure 6-14. The problem of Figure 6-8 using the nonuniform field specification option.

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Figure 6-15. Data cards for the problem in Figure 6-8 with $E_m = 1 V/m$, $\Theta_E = 0^{-90}$, $\Phi_p = 90^{-90}$, FSO=2 (cont.)

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Figure 6-15. Data cards for the problem in Figure 6-8 with $E_m = 1 \text{ V/m}, \Theta_E = 0^\circ, \Theta_p = 90^\circ, \Phi_p = 90^\circ, \text{FSO}=2.$

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<u> Martin Martin Martin</u>

$E_{m} = 1, \Theta_{E} = 0, \Theta_{p} = 90, \phi_{p} = 90$

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<u>Serence</u>

f = 7157018.74 Hz (k $z \approx 1.5$)

nopulting and the provided is report but the second of the second to replace the function of the second second

$$I_{1}(0) = 1.216E-5 / 17.18 \qquad I_{1}(1) = 1.572E-5 / -49.19$$

$$I_{2}(0) = 6.708E-5 / -13.76 \qquad I_{2}(1) = 2.849E-5 / -129.84$$

Figure 6-16. The problem of Figure 6-8 using the nonuniform field specification option.

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VII. SUMMARY

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A digital computer program, WIRE, which is designed to compute the terminal currents induced in a multiconductor transmission line by a single frequency, incident electromagnetic field has been described. The transmission line consists of n wires (cylindrical conductors) and a reference conductor. The reference conductor may be a wire (TYPE=1), an infinite ground plane (TYPE=2) or an overall, cylindrical shield (TYPE=3). All (n+1) conductors are assumed to be perfect conductors and the surrounding medium is assumed to be linear, isotropic, homogeneous and lossless. The line is assumed to be uniform in that all (n+1) conductors have no variation in their cross-sections along the line length and are parallel to each other.

Two types of incident field specification are provided for. Uniform plane wave excitation can be specified for TYPE 1 and TYPE 2 structures whereas nonuniform field excitation can be specified for all structure types.

The primary restrictions on the program validity is that the crosssectional dimensions of the line, e.g., wire spacings, must be electrically small and the smallest ratio of wire separation to wire radius must be larger than approximately 5.

General linear termination networks are provided for at the two ends of the line.

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APPENDIX A

A Note on Common Mode and Differential Mode

Currents

An important assumption in this method is that the sum of the currents in all (n+1) conductors at a particular x along the line is equal to zero. This is the conventional notion of transmission line currents. The purpose of this Appendix is to provide some justification for the assumption.

As a prelude, consider the two conductor line (n=1) shown in Figure A-1(a). At a particular longitudinal coordinate, x, we have separated the total current into a common mode component, I_C , and a differential mode component, I_D . This is purely a mathematical operation and given the currents $I_1(x)$ and $I_0(x)$, one can always resolve them into these components as shown by the following. We are simply looking for a unique transformation which performs this separation. If we write

$$I_{1}(x) = I_{C}(x) + I_{D}(x)$$
 (A-la)

$$I_2(x) = I_C(x) - I_D(x)$$
 (A-1b)

then in matrix form the equations become

$$\begin{bmatrix} I_1(\mathbf{x}) \\ I_2(\mathbf{x}) \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ -1 & 1 \\ \vdots \end{bmatrix} \begin{bmatrix} I_D(\mathbf{x}) \\ I_C(\mathbf{x}) \end{bmatrix}$$
(A-2)

The essential question here is whether T is nonsingular which would represent \tilde{a} a unique transformation between the two sets of currents. Clearly T is



(a) n = 1



Figure A-1. Illustration of common mode and differential mode currents.

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nonsingular and we may write (multiplying (A-2) on the left by T^{-1})

the second se

$$\begin{bmatrix} I_{D}(x) \\ I_{C}(x) \end{bmatrix} = \frac{1}{2} \begin{bmatrix} 1 & -1 \\ 1 & 1 \end{bmatrix} \begin{bmatrix} I_{1}(x) \\ I_{2}(x) \end{bmatrix}$$
(A-3)

Therefore, given $I_1(x)$ and $I_2(x)$ for a particular x, one can uniquely determine $I_D(x)$ and $I_C(x)$.

The question of physical significance of $I_{\rm D}$ and $I_{\rm C}$ is essentially irrelevant since this is merely a transformation of variables. The essential point is that as far as the terminal responses are concerned, we need only consider the differential mode (transmission line type) current, I_n , since the common mode current (commonly called antenna type current) has essentially no effect on the terminal responses. The justification for this statement lies in our fundamental assumption that the cross-sectional dimensions (wire separation) of the line are much less than a wavelength. Therefore we may consider the terminal impedances (Z₀ and Z_{χ}) as lumped and if we apply Kirchoff's current law to the "nodes" containing the impedance we can only conclude that the common mode current is zero at the endpoints of the line, i.e., $I_{c}(0) = I_{c}(z) = 0$. At points along the line, this is not generally true and the line currents will not be simply due to the differential mode current but will be a combination of $I_{D}(x)$ and $I_{C}(x)$ as shown in Figure A-1(a). The essential point here is that if we are only interested in computing the terminal response of the line (as we are in this report), we may disregard or omit consideration of the common mode current.

The extension of this result to multiconductor lines is quite similar. Consider Figure A--1(b) where we have decomposed each line current into a

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differential mode current, I_{Di} , and a common mode current, I_C . Note that we have taken the common mode currents to be the same at corresponding points (values of the x coordinate) along the line in all line conductors. The justification for this is our primary assumption that the maximum crosssectional dimension of the line is "electrically small", i.e., much less than a wavelength. The essential question here is whether we can define a unique (nonsingular) transformation between the actual line currents, I_0 , I_1 , ----, I_n , and the decomposition components, I_{D1} , I_{D2} , ---, I_{Dn} , I_C . This is easily found from Figure A-1(b) from

$$I_{n}(x) = I_{C}(x) + I_{Dn}(x)$$

$$I_{i}(x) = I_{C}(x) + I_{Di}(x)$$

$$(A-4)$$

$$I_{1}(x) = I_{C}(x) + I_{D1}(x)$$

$$I_{0}(x) = I_{C}(x) - \sum_{i=1}^{n} I_{Di}(x)$$

which becomes in matrix notation



One can easily show (use elementary row operations to reduce T to echelon or upper diagonal form) that T is nonsingular and therefore represents a unique transformation. Thus for a particular x, given the actual line curients, $I_n(x)$, ..., $I_1(x)$, $\underline{I}_0(x)$, one can obtain the components, $I_{Dn}(x)$, ..., $I_{D1}(x)$, $I_c(x)$ from

$$\begin{bmatrix} I_{Dn}(x) \\ \vdots \\ I_{Di}(x) \\ \vdots \\ I_{D1}(x) \\ I_{c}(x) \end{bmatrix} = T^{-1} \begin{bmatrix} I_{n}(x) \\ \vdots \\ I_{1}(x) \\ \vdots \\ I_{1}(x) \\ I_{0}(x) \end{bmatrix}$$
(A-6)

Again, assuming the line cross-sectional dimensions to be electrically small, we may conclude that the common mode currents at the endpoints of the line, $I_{c}(0)$ and $I_{c}(z)$, are essentially zero and have no effect on the terminal networks. Therefore it suffices to consider only the differential mode (transmission line mode) currents when computing only the terminal responses of the line.

For a parallel discussion of this problem see [14].

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APPENDIX B

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WIRE

Program Listing

Flowchart

WIRE0002 WIRE0003 PROGRAM WIRE (FORTRAN IV, DOUBLE PRECISION) WIRE0004 WRITTEN BY WIRE0005 CLAYTON R. PAUL DEPARTMENT OF ELECTRICAL ENGINEERING WIRE0006 #TRE0007 UNIVERSITY OF KENTUCKY WIRE0008 LEXINGTON, KENTUCKY 40506 WIRE0009 **WIRE0010** A DIGITAL COMPUTER PROGRAM TO COMPUTE THE TERMINAL CURRENTS WIRE0011 AT THE ENDS OF A MULTICONDUCTOR TRANSMISSION LINE WHICH IS WIBE0012 EXCITED BY AN INCIDENT ELECTRONAGNETIC FIELD. WIREO013 **WTRE0014** THE DISTRIBUTED PARAMETER, NULTICONDUCTOR TRANSMISSION LINE WIRE0015 EQUATIONS ARE SOLVED FOR STEADY STATE, SINUSOIDAL EXCITATION WIREO016 **WIRE0017** OP THE LINE. **WIRE0018** THE LINE CONSISTS OF N WIRES (CYLINDRICAL CONDUCTORS) AND A WIRE0019 REFERENCE CONDUCTOR. THE REFERENCE CONDUCTOR MAY BE A WIRE WIREO020 (TYPE=1), AN INFINITE GROUND PLANE (TYPE=2), OR AN OVERALL WIRE0021 CYLINDRIGAL SHIELD (TYPE=3). WIRE0022 WIREO023 THE INCIDENT FIELD NAY BE IN THE FORM OF A UNIFORM PLANE WAVE WIRE0024 FOR TYPE 1 AND TYPE 2 STRUCTURES OR A NONUNIFORM FIELD FOR ALL WIRE0025 STRUCTURE TYPES. WIREO026 WIREO027 THE N WIRES ARE ASSUMED TO BE PARALLEL TO EACH OTHER AND THE WIRE0028 REFERENCE CONDUCTOR. WIRE0029 WIREO030 THE N WIRES AND THE REFERENCE CONDUCTOR ARE ASSUNED TO BE **WIRE0031** PERFECT CONDUCTORS. WIREO032 WIRE0033 THE LINE IS INMERSED IN A LINEAR, ISOTROPIC, AND HOMOGENEOUS WIRE0034 MEDIUN WITH A RELATIVE PERNEABILITY OF NUR AND A RELATIVE #TRE0035 DIELECTRIC CONSTANT OF ER. THE MEDIUM IS ASSUMED TO BE LOSSLESS. WIRE0036 **WTRE0037** LOAD STRUCTURE OPTION (LSO) DEFINITIONS: LSO=11, THEVENIN EQUIVALENT LOAD STRUCTURES WITH DIAGONAL ¥TRE0038 **WIRE0039** IMPEDANCE MATRICES WIRE0040 LSO= 12, THEVENIN EQUIVALENT LOAD STRUCTURES WITH FULL WIREO041 IMPEDANCE MATRICES WIRECOU? LSO=21, NORTON EQUIVALENT LOAD STRUCTURES WITH DIAGONAL WIRE0043 ADMITTANCE MATRICES WIRE0044 LSO=22, NORTON EQUIVALENT LOAD STRUCTURES WITH FULL WTRECOUS. ADNITTANCE MATRICES WIRE0046 WIRE0047 FIELD SPECIFICATION OPTION (PSO) DEFINITIONS: WIRE0048 PSO= 1, UNIFORM PLANE WAVE (TYPE=1,2) WIRE0049 PSO=2, NONUNIFORM FIELD (TYPE=1,2,3) WIRE0050 WIRE0051 PUNCTION SUBPROGRAMS USED: E1.E2 VIRE0052 SUBROUTINES USED: LEOTIC WIRE0053 ¥1 RE0054 WIRE0056 ALL VECTORS AND MATRICES IN THE POLLOWING DIMENSION STATEMENTS WIRE0057 С SHOULD BE OF SIZE N WHERE N IS THE NUMBER OF WIRES (EXCLUSIVE OF WIRE0058 THE REPERENCE CONDUCTOR), I.E., V1(N), V2(N), V0(N,N), VL(N,N), B(N), WIRE0059 C A(N, N), WA(N), M1(N, N), M2(N, N), ETL(N), ETO(N), M3(N, N), V3(N), V4(N)WIRE0060 C WIRE0061

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INPLICIT REAL+8 (A-H,0-Z)
                                                                                       WIRE0062
       INTEGER TYPE, FSO
                                                                                       WIRE0063
       REAL+8 L, V3( 2), V4( 2), IOH, ILH, IOR, IOI, ILR, ILI, IOA, ILA, HUR, HUO2PI WIRE0064
      1,HI,NI,NH,NP
                                                                                       WIREQ065
     COMPLEX+16 XJ, V1 ( 2), V2 ( 2), V0 ( 2, 2), XL ( 2, 2), A ( 2, 2), B ( 2), WIRE0066
1SUH0, SUHL, IO, IL, ZEROC, WA ( 2), H1 ( 2, 2), H2 ( 2, 2), ETL ( 2), ETO ( 2), WIRE0067
2C, A1, A2, OWEC, H3 ( 2, 2), EBXL, EBL, V1H, V2H, EP, EW, EJEZ, EBTPBZ, EPBL, WIRE0068
      3 ENBL, BJCI, SUMC, SUMS, BLOC, BLOS, B1, B2, BJBY
                                                                                       WIRECO69
       CONHON XJ, ZERO, TWO, ONE, ONEC
                                                                                       WIRE0070
       DATA CHTH/2.54D-5/, HU02PI/2.D-7/,P5/.5D0/,FOUR/4.D0/,
                                                                                       WIRE0071
      10N E80/180. D0/. V/2. 997925D8/
                                                                                       WIRE0072
       22R0=0.D0
                                                                                       WIRBO073
                                                                                       STREOO74
       ON E= 1. DO
       T#0=2.D0
                                                                                       WIRE0075
       ON EC=DCHPLE(1.D0.0.D0)
                                                                                        WIREO076
       2BROC= DCHPLX (0. D0, 0. D0)
                                                                                        WIREO077
       IJ=DCHPLX (0. D0, 1. D0)
                                                                                       WIRE0078
       PI=POUR+DATAN (ONE)
                                                                                       WIRE0079
       RADEG=ONE80/PI
                                                                                       WIREO080
                                                                                       WIRE0081
WTRR0083
       READ AND PRINT INPUT DATA
                                                                                       WIRECO84
                                                                                        WIRE0085
       READ (5,1) TYPE, LSO, PRO, H, ER, HUR, L
                                                                                        WIRE0086
     1 FORMAT (9X, 11, 8X, 12, 9X, 11, 8X, 12, 3 (810.3))
                                                                                        WIRE0087
       IF (TYPE, GE. 1. AND. TYPE. LE. 3) GO TO 3
                                                                                        WIRE0088
     WRITE(6,2)
2 FORMAT (* STRUCTURE TYPE ERROR*//* TYPE MUST EQUAL 1,2,08 3*///)
                                                                                        WIRE0089
                                                                                        WIREO090
       GO TO 121
                                                                                        WIRE0091
     3 IF (LSO. EQ. 11. OR. LSO. EQ. 12) GO TO 5
                                                                                        WIRE0092
       IF (LSO. EQ. 21. OR. LSO. EQ. 22) GO TO 5
                                                                                        #TRR0093
                                                                                        WIRE0094
       WRITE (6, 4)
     4 POBNAT (* LOAD STRUCTURE OPTION BRROR ///*
                                                            LSO MUST BQUAL 11, 12, 2WIRE0095
      11,08 22 ///)
                                                                                        VIRE0096
       GO TO 121
                                                                                        WIRE0097
     5 IF (FSO. EQ. 1. OR. FSO. EQ. 2) GO TO 7
                                                                                        WIRECO98
       WRITE (6, 6)
                                                                                        VIREO099
     6 POBNAT (* FIELD SPECIFICATION OPTION BEROR'//*
                                                                   PSO MUST EQUAL 1, VIREO100
      1 OB 2*///)
                                                                                        EIRE0101
       GO TO 121
                                                                                        WIRE0102
     7 IF (TYPE. BQ. 3. AND. PSO. EQ. 1) GO TO 8
                                                                                        WIREO103
       GO TO 10
                                                                                        WIRE0104
     8 WRITE (6,9)
                                                                                        WIRE0105
     9 PORNAT ( UNIFORM PLANE WAVE EXCITATION CANNOT BE SPECIFIED FOR THEWIREO106
      1 TYPE 3 STRUCTURE'///)
                                                                                        WIRE0107
       GO TO 121
                                                                                        WIRE0108
    10 WRITE(6,11) N.TYPE,LSO,PSO,L.ER. MUR
                                                                                        WTRR0109
    11 FORMAT (361, 51X, 'WIRE'///
                                                                                        WIRE0110
      145X, 12, ' PARALLEL WIRES'///
                                                                                        WIRE0111
      243I. TTPE OF STRUCTURE= ',I1///
341I. LOAD STRUCTURE OPTION= ',I2///
                                                                                        WIRE0112
                                                                                        WIRE0113
      440X, * PIELD SPECIFICATION OPTION= *, I1///
                                                                                        WIRE0114
      539X, 'LINE LENGTH= ', 1PE13.6, 'METERS'//
633X, 'DJELECTRIC CONSTANT OF THE MEDIUM= ', 1PE10.3///
733X, 'RELATIVE PERMEABILITY OF THE MEDIUM= ', 1PE10.3///)
                                                                                        HIRE0115
                                                                                        WIRE0116
                                                                                        WIRE0117
    GO TO (12,20,16), TYPE
12 READ (5,13) RWO
                                                                                        WIRE0118
                                                                                        WTRE0119
    13 FORMAT (5X, 810.3)
                                                                                        WIRE0120
        WRITE (6, 14) RWO
                                                                                         WIRE0121
    14 FORMAT (* REPERENCE CONDUCTOR FOR LINE VOLTAGES IS A WIRE WITH RADIWIRBO122
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105= ', 1PE10. 3. ' BILS'////	WIRE0123
RWO=RWO+CHTH	WIRE0124
WRITE(6,15)	WIRE0125
15 POBHAT (' WIRE NUMBER', 41, WIRE RADIUS (MILS) ', 181,	WIRE0126
1'Z COORDINATE (NETERS)', 241, 'Y COORDINATE (NETERS)',//)	WIRE0127
GO TO 23	WIRE0128
16 READ (5, 17) RS	WIRBO129
17 FORNAT (5X, B10.3)	WIRE0130
WRITE(6, 18) RS	WIREU131
TE FORMAT (* REFERENCE CONDUCTOR FOR LINE VOLTAGES IS A CILINDRI	CAL UVWIKEVIJZ
IERALL SHIELD WITH INTERIOR RADIUS= ', VEBIU, J,' NETERS'////)	W1850133
R52=R5=R5 #6 Tee /(WIRDV134
TALIS(0, 17) 10 PADRAT/I UTDE HARREI 27 INTER BAATAS (HTICAI, 27, ICEDADATA	N RETWEETER136
1PPN HTPP AND CPFTPP OF SHTRLD /NATEDS (TE (DENTERO137
2GREES ///	WIRE0138
GO TO 23	WIRBO139
20 WRITE (6, 21)	WIRE0140
21 FORMAT (* REFERENCE CONDUCTOR FOR LINE VOLTAGES IS AN INFINIT	E GROUWIRE0141
1WD PLANE'////)	WIRB0142
WRITE(6,22)	WIRE0143
22 FORMAT (' WIRE NUNBER', 4X, 'WIRE RADIUS (MILS) ', 18X,	WIRE0144
1'HORJZONTAL COORDINATE (NETERS)', 16X, WIRE HEIGHT (NETERS)'/	/) WIRE0145
	WIRE0146
READ AND PRINT LINE DIMENSIONS AND COMPUTE THE CHARACTERISTI	C WIRBOI47
INPEDANCE MATRIX, ZC (STORE ZC IN REAL PART OF ARRAY NI)	WIREU140
	#185V147
23 C= NUCZEI+C#BEC+++DSQR1(NUK/DB)	WIREUIJU WIREUIJU
DV 67 5.178	WT BEA152
	WTRE0153
HRITE(6.25) I.RU.S.Y	WIRR0154
25 FORMAT (21, 12, 131, 19810.3, 271, 19810.3, 351, 19810.3/)	WIRE0155
¥3 (I)=#	WIRE0156
¥4 (I) = Y	WIRBO157
R¥=R¥+CHTH	WIRE0158
GO TO (26, 27, 28), TYPE	WIRBO159
26 DI2=2+2+1+1	WIRE0160
N1 (I,I) *C*DLOG (D12/(RW*RWU))	#1#50101
GU TU JY 37 HI/T TICADIOC/48047/281	WIREV 102
27 m (1,1) = 0 m (1,	WTRE0164
28 81 (T.3) = C+DLOG ((BS2-2+2) / (BS+RW))	WIRE0165
29 CONTINUE	WIRE0166
IF (N. EQ. 1) GO TO 34	WIRE0167
K1=N-1	WIRE0168
DO 33 I=1,K1	WIRE0169
K2=I+1	WIRBO170
DO 33 J=K2,H	WIRBO171
	WIREU172
₩T_#D (J)	#18501/J 818501/J
11-14(1) V(=V4(1)	WI 8501/4 NT 820176
GO TO (30.31.32) TYPE	WTRR0176
30 DI2=ZI+ZI+YI+YI	VIREO177
DJ2=ZJ+ZJ+ ZJ+ YJ	WIRE0178
2D=2I-2J	WIRE0179
YD=YI-YJ	WIRE0180
DIJ2=ZD+ZD+YD+YD	WIRE0181
N1 (I,J) =P5+C+DLOG(DI2+DJ2/(R₩9+R₩0+DIJ2))	WIR80182
H1 (J,I) = H1 (I,J)	WIREO183

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		GO TO 33	WIRE0184
	31	2D=2I-2J	WIRE0185
		YD=YI-YJ	WIRE0186
		DIJ2=ZD+ZD+YD+YD	WIRE0187
		$M1 (T_J) = P5 + C + DLOG (ON E + POUR + Y T + YJ/DTJ2)$	TRE0188
		$M_1(J_1, T) = M_1(T_1, J)$	WIRE0189
			WIRE0190
	32	THETA= $(YT-YI)$ /RADEG	WIRE0191
			WTRE0192
			WTRE0193
			WTRE0194
	1	$\Pi = \{\mathbf{x}, \mathbf{y}, \mathbf{y}, \mathbf{y}, \mathbf{z}, \mathbf{y}, \mathbf{z}, \mathbf{y}, \mathbf{z}, \mathbf{z},$	WTRF0195
		MIAINAN ANTIN	WTRPA196
	32		WTRF0197
c	33	CON11802	WTRR0198
č		CONDITING THE THEORY OF THE CHARACTERTS THORNAUCE MATERY 20140	WIDE0190
č		CONFULE INFERSE OF THE CHARACTERISTIC INFERRACE BATHINGSCON	WIND0777
č		CIURD ACTIV IN ANARIS IIZ AND IS	WTRF0200
C	2/1	NO 26 T-1 N	WT DP0207
			91 890202 91 890202
			WIRE0203
	25		WIN50204
	30	$B_2(1,3) = 2EBOC$	WIRE020
	30		W1850200
		CALL LEGTIC (A, N, N, H2, N, N, O, WA, KER)	WIRE0207
			WIREUZUB
		DO(3) L=1, N	WIREOZU4
		DO 37 J=1,N	WIREUZIU
	31	$A_3(1,3) = B_2(1,3)$	WIREUZII
		IF (RER. NE. 1) GO TO 39	WIRFO212
		WRITE(6, 38)	WIREO213
	. 4	FORMAT (//, * *****CHARACTERISTIC INPEDANCE HATRIX INVERSION ERROR**	WIREO214
			WIRE0215
		GO TO 121	WIREO216
С			WIREO217
C		READ AND PRINT ENTRIES IN LOAD ADMITTANCE (IMPEDANCE) MATRICES	WIRE0718
С		(STORE ADMITTANCE (INPEDANCE) MATRICES AT X=0 IN ARRAY YO AND	WIREO219
С		THOSE AT X≠L IN ARRAY ¥L)	WIRE0220
С			WIRE0221
	39	IP (LSU. EQ. 11. OR. LSJ. EQ. 12) GO TO 42	WIRE0222
		WPITE(6,40)	WIRE0223
	40	PORMAT (//, 18X, "ADMITTANCE AT X=0", 43X, "ADMITTANCE AT X=L"/)	WIRE0224
		WRITE(6,41)	WIRE0225
	41	PORMAT (211, * (SIEMENS) *, 511, * (SIEMENS) */)	WIRE0226
		GO TO 45	WIRE0227
	42	WRITE (6, 43)	WIRE0228
	43	FORNAT (//, 18K, "IMPEDANCE AT X=0",44X,"IMPEDANCE AT X=L"/)	WIRE0229
		WRITE(6,44)	WIRE0230
	44	FORNAT (23X, " (OHMS) ", 54X, " (OHMS) "/)	WIRE0231
	45	¥RITE(6,46)	WIRE0232
	46	FORMAT (* ENTRY*, 10X, *REAL*, 11X, *IMAG*, 41X, *REAL*, 11X, *IMAG*//)	WIRE0233
		DO 49 I≈1,N	WIRE0234
		READ (5,47) YOR, YOI, YLR, YLI	WIREQ235
	47	FORMAT (2 (E10. 3), 20X, 2 (E10. 3))	WIRE0236
		YO (I,I) = YOR + KJ + YOI	WIRE0237
		YL (I,I) = YLR+XJ+YLI	WIRE0238
		WRITE(6,48) I,I,YO(I,I),YL(I,I)	WIRE0239
	48	FORMAT (1X, I2, 2X, I2, 2 (5X, 1PE10. 3), 30X, 2 (5X, 1PE10. 3) /)	WIRE0240
	49	CONTINUE	WIRE0241
		IP (LSO.EQ. 11.OR.LSO.EQ.21) GO TO 52	WIRE0242
		IF (N. EQ. 1) GO TO 52	W1RE0243
		DO 51 I = 1.K1	WIRE0244

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		K2=T ▲ 1	WTRE0245
		DO = 51 J = K2 N	WTRE0246
		READ (5.50) YOR YOF YER YET	WTRE0247
	50	FORMAT (2 (E 10. 3) . 20K. 2 (E 10. 3))	WIRE0248
		YO(I.J) = YOR + XJ + YOI	WIRE0249
		YL(I,J) = YLR + XJ + YLI	WIRE0250
		YO(J,I) = YO(I,J)	WIRE0251
		YL(J,I) = YL(I,J)	WIRE0252
		WRITE (6,48) I.J. YO (I.J), YL (I.J)	WIRE0253
	51	CONTINUE	WIRE0254
С			WIRE0255
С		IF THEVENIN EQUIVALENT SPECIFIED, SWAP ENTRIES IN ARRAYS N1 AND	M2WIRE0256
С		HI WILL CONTAIN THE INVERSE OF ZC AND N2 WILL CONTAIN ZC	WIRE0257
С			WIRE0258
	52	IF (LSO. EQ. 21. OR. LSO. EQ. 22) GO TO 54	WIRE0259
		DO 53 I=1,N	WIRE0260
		DO 53 J=I,N	WIRE0261
		A1=H1(I,J)	WIRE0262
		A 2=M2 (I, J)	WIRE0263
		$n_1(\mathbf{I},\mathbf{J}) \neq n_2$	WIRE0264
		$\frac{1}{1} (J, I) = \lambda 2$	WIREU205
	F N	Π2(I,J) ≠Λ1	W1RE0266
~	23	N2 (J, 1) = A1	WINEU207
C			WIKEV200
Č		CONFUTE THE NATHIX SC+SL+SCINV+SU FOR THE THEVENIN EQUIVALENT	W1RE0209
Č		CHODE IN FORM FOR NORION EQUIVELENT	WIREV270
č		STURE IN ARRAY NZ	WIREVZ/I
C	5 11	TP (1 CO PO 13 OD 1 CO PO 33) CO MO 57	WIND0272
	24	$\frac{11}{10} \frac{12}{10} \frac{12}{10} \frac{12}{10} \frac{10}{10} 10$	NIREV2/J NIREV2/J
		DO 55 1-1 W	WIREV2/4
	55		WIRE0273
	,,,		WT 920270
		$p_0 = 56 = 1 \text{ m}$	WT PP0278
	56	$N_2 / T_{-1} = V_1 / T_{-1} + A / T_{-1} + N_2 / T_{-1}$	WT 8P0279
	50		WT820280
	57	DO 59 T=1.W	WIRE0281
		DU 59 J=1.N	WTRE0282
		SUNL=ZBROC	WIRE0283
		DO 58 K= 1.N	WIRE0284
	58	SUML = SUML + H1 (I, K) + TO (K, J)	WIRE0285
	59	A(I,J) = SUBL	WIRE0286
		DO 61 I=1,N	WIRE0287
		DO 61 $J=1, N$	WIRE0288
		SUNL=2 EROC	WIRE0289
		DO 60 K=1,N	WIRE0290
	60	SUML=SUML+YL(I,K)*A(K,J)	WIRE0291
	61	H2 (I,J) = SUHL+H2 (I,J)	WIRE0292
	62	BB=TWO+PI+DSQRT(ER+HUR)/V	WIRE0293
		BBL=BB + L	WIRE0294
C			WIRE0295
C		LY FIELD SPECIFICATION IS A UNIFORM PLANE WAVE, READ DATA AND	WIREO296
C		COMPUTE THE COMPONENTS OF THE ELECTRIC FIELD INTENSITY AND THE	WIRE0297
C		PHASE CONSTANT (FOR ONE HERTZ) IN THE X,Y, AND Z DIRECTIONS	WIREO298
С			WIRBO299
		17 (730, 20, 2) GU TU 00	W1KE0300
	67	REAU(3,03) ER,THE,THE,THE	MIKE0301
	03	- ΓυκπΑι (4 (6 Ιυ. 5, 3λ)) υρταρίε (4)	MI420305
	e 11	RALIE(0,04) Robbin//// Rectminton composito i unipode dine unupi ()	MIKENJA'
	04	DIADETY (22) DR AND AND DAD DAD COULD TO V DATENUU RPANE MAAE,//}	W105V3V4 W105V3V4
		wuitefotost eutreetactac	#1420303

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65 FORMAT (* MAGNITUDE OF ELECTRIC FIELD = *, 1PE 10.3, * (VOLTS/NETER) */ WIRE0306
    1* THETAE = ', 1PE10.3, ' (DEGREES) '/' THETAP = ', 1PE10.3, ' (DEGREES) '/WIRE0307
2* PHIP = ', 1PE10.3, ' (DEGREES) '///) WIRE0308
      THE=THE/RADEG
                                                                            WIRE0309
      THP=THP/RADEG
                                                                            WIRE0310
      PHP=PHP/PADEG
                                                                            WIRE0311
      CTE=DCOS (THE)
                                                                            WIRE0312
      CTP=DCOS (THP)
                                                                            WIRE0313
                                                                            WIREO314
      CPP=DCOS (PHP)
      STE=DSIN (THE)
                                                                            WIRE0315
      STP=DSIN (THP)
                                                                            WIRE0316
      SPP=DSI# (PHP)
                                                                            WIRE0317
      BYN=BN+CTE+STP
                                                                            WIRE0318
      EZA=-EA* (CTE*CTP*CPP-STE*SPP)
                                                                            WIRE0319
      BIN=-BN* (CTE*CTP*SPP+STE*CPP)
                                                                            WIREO320
      BBX=BB*STP*SPP
                                                                            WIRE0321
      BBY=BB*CTP
                                                                            WIRE0322
      BB2=BB+STP+CPP
                                                                            WIRE0323
                                                                            WIRE0324
WIRE0326
С
   66 CONTINUE
                                                                            WIRE0327
   READ (5,67, END=121) F
67 FORMAT (E10.3)
                                                                            WIRE0328
                                                                            WIRE0329
      BETA=BB+F
                                                                            WIRE0330
      BETAL=BEL*P
                                                                            WIRE0331
      DS=DSIN(BETAL)
                                                                            WTRE0332
      DC=DCOS(BETAL)
                                                                            WIRE0333
      GO TO (68,74),750
                                                                            WIRE0334
                                                                            WIRE0335
C
Ċ
      COMPUTE THE EQUIVALENT FORCING FUNCTIONS FOR UNIFORM PLANE WAVE
                                                                            WIRE0336
Ċ
      BICITATION
                                                                            WTRE0337
C
C
                                                                            WIRE0338
      CONPUTE THE X,Y, AND Z COMPONENTS OF THE PHASE CONSTANT FOR
                                                                            WIRE0339
С
      UNIFORM PLANE WAVE EXCITATION AND A PREQUENCY OF F HERTZ
                                                                            WIRE0340
                                                                            WIRE0341
С
   68 BX=BBX+F
                                                                             WIRE0342
                                                                            WIREO343
      BY=BBY+P
      BX=BB2*F
                                                                             WIRE0344
      BBXL=CDEXP (-XJ+BX+L)
                                                                             WIRE0345
      BP=BETA+BI
                                                                             WTRE0346 .
      BH=BRTA-BX
                                                                             WIRE0347
      BPBL=CDEXP (XJ+BETAL)
                                                                             WIRE0348
      BEBL=CDEXP (-XJ+BETAL)
                                                                             UTRE0349
      EP=EPBL+ #2 (SERO, L,-BP)
                                                                             WIRE0350
      EN=ENBL+ E2 (Z BRO, L, BN)
                                                                             WIRE0351
   69 GO TO (70,72), TYPE
                                                                             WIRE0352
                                                                             WIRE0353
С
Ċ
       COMPUTE FORCING PUNCTIONS FOR UNIFORM PLANE WAVE EXCITATION AND
                                                                             WIRE0354
С
      TYPE I STRUCTURES
                                                                             HIRE0355
С
                                                                             WIRE0356
   70 DO 71 I=1,#
                                                                             WIRE0357
      YI=V4(I)
                                                                             #TR20358
       2I=V3(I)
                                                                             WIRE0359
       BYPBZ=BY+YI+3Z+ZI
                                                                             WIRE0360
       BAYPBZ=CDEXP (-XJ+BYPBZ) -ONE
                                                                             WTRE0361
       BJBZ=CDEXP (-XJ+BZ+ZI)
                                                                             WIRE0362
       EJBY=CDEXP (-IJ+BY+YI)
                                                                             WIRE0363
       VIN=EXN+EBYPB2/TWO
                                                                             WIRE0364
       ¥2H=-XJ+¥1H
                                                                             WIRE0365
       ¥1 (I) = ¥18+ (BP+EN)
                                                                             WIRR0366
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		V2 (I) = V2 M+ (EP-EN)	WIRE0367
		ETO (I) = (EYN+YI+EZN+ZI) +E2 (ZEBO, ONE, - BYPBZ)	WIRE0368
	71	ETL(I)=ETO(I)*PBXL	WIRE0369
		GO TO 96	WIRE0370
C			WIRE0371
С		COMPUTE FORCING FUNCTIONS FOR UNIFORM PLANE WAVE EXCITATION AND	WIRE0372
С		TYPE 2 STRUCTURES	WIRE0373
С			WIBE0374
	72	DO 73 I=1,M	WIRE0375
		¥I=¥4(I)	WIRE0376
		21=V3(1)	WIRBO377
		SBY=DSIN (BY+YI)	WIRE0378
		EJ BZ=C DE XP (- XJ * B Z * ZI)	WIRE0379
		V2M=~BXM+EJBZ+SBY	WIRE0380
		V1M=XJ+V2N	WIRE0381
		V1 (I) = V10+ (EP+EN)	WIRE0382
		¥2(I) = ¥2H+(EP-EN)	ATSE0383
		ETO(I) = EYN + EJBZ + EZ(-YI, YI, BY)	VIREO384
	73	ETL(I) = BTO(I) + EBXL	WIRE0385
		GO TO 96	WIRE0386
С			WIRE0387
С		COMPUTE THE EQUIVALENT FORCING FUNCTIONS FOR NONUNIFORM EXCITATION	WIREC388
С	_		WIRE0389
	74	EPBL=CDEXP(XJ+BETAL)	WIRE0390
		ENBL=CDEXP(-XJ+BETAL)	WIRE0391
		WRITE(6,75)	WIRE0392
	75	FORMAT (///* EXCITATION SUBRCE IS A NONUNIFORM FIELD*//)	WIRE0393
		GO TO (76,83,83), TYPE	WIRE0394
С			WIRE0395
С		COMPUTE THE CONTRIBUTION DUE TO THE LONGITUDINAL ELECTRIC FIELD	WIRE0396
С		FOR THE REPERENCE WIRE	WIRE0397
С			WIRE0398
	76	READ (5,77) NLO, EO, TO	WIRE0399
	77	FOREAT (I 10,2 (10X,E10.3))	WIREC400
		WRITE(6,78)	WIRE0401
	78	PORMAT (* LONGITUDINAL ELECTRIC PIELD ON REPERENCE WIRE*/)	WIRE0402
		#RITE(6,79)	WIRE0403
	79	FORMAT (51, SPECIFICATION POINT (HETERS) ",	WIRE0404
		15%, 'BLECTRIC FIELD INTENSITY (VOLTS/METER) ', 5%, 'PHASE (DEGREES) '//)	WIRB0405
		IL=ZERO	WIRB0406
		EL=E0	WIRE0407
		TL=TO	WIRE0408
		SUHC=ZEROC	WIRE0409
		SUHS=ZEROC	WIRE0410
		WRITE(6,80) XL,E0,TO	WIRE0411
	80	FORMAT (13X, 1PE 10.3, 24X, 1PE 10.3, 25X, 1PE 10.3)	WIRE0412
			WIRE0413
	~ *	READ (5,81) II, EL, TI	WIREO414
	81	FORMAT (3 (E 10.3, 10X))	WINEO4 15
		WRITE(6,80) XI,81,71	WIKEU416
			WIRE0417
		58 = 51 AD - AT	ATKENA 18
		12-11 12-11	WIREU419
		AV+AE-1L MT-/BD-BT1/YD	WIRSV420
		ni=(cr=cu)/iU pr_/prayn_prayn/yr	#1850921 97980#33
		DI+ (CL-AF-DF-AL)/AV NT- (MD_MT) //DID#C+VD)	WLR5U422
		RI~ (IF-ID)/ (RAUDUTAD) CT~ (RT #VD_#DAVI) //DINDC#VN)	NIRSU423
		UL- (16787717786) / (88069780) Nu-vit-dema	8185V424 91890435
		HO-NIA DHI	W1850423 UTDPA#34
		#101-031# #101-031#	WIRDU420

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		SUNC=SUNC+EJCI+P5+(NI+EPBL+E1(XL,XP,NN)+NI+ENBL+E1(XL,XP,NP)	WIRE0428
	1	ART#PORT#P7/TT YO WALART#PWRT#P7/TT YO MDLL	WTPP0#20
		(V) I + BE DA + BE (AL, AE, WA, V) + DL + BADL + BE (AL, AF, WE))	
		SUAS=SUAS-XJ=P5=EJCI=(AI=PBL=P1(XL,XP,AA)-AI=BL=P1(XL,XP,NP)	WIRE0430
	1	I+BI+EPBL+E2(XL,XP,NN)-BI+ENBL+E2(XL,XP,NP))	WIREO431
			HTDPON 32
			#1850432
		RT=R6	WIRE0435
	82	TL=TP	WIRE0434
			STERAN 35
			WIREO4JJ
		ELUS#5UAS	WIRE0436
		GO TO 84	WIRE0437
	83	Pt 0C=7 PpoC	UTOFGU 38
	0.3		
		ELUS=ZEBOC	WIRE0433
С			WIRE0440
C		CONDITE THE CONTRIBUTION DUE TO THE LONGITUDINAL FLECTRIC STELD.	WIRFOMM1
2		Was and the contraction and to the bonder opened appointed trade	02000447
C		FOR THE WIRES	MTREA47
С			WIRE0443
	84	DO 95 T≠1.¥	WTRE0444
	•••		NT 020// #5
		READ (5,65) REU, ELU, ILU	RINGU44D
	85	FORNAT (I 10,2 (10X, B10.3))	WIRE0446
		XL=ZERO	#TPE0447
			UY OPAUNO
		WF116(0,00) 1	#1850440
	86	FORMAT (// LONGITUDINAL ELECTRIC FIELD ON WIRE ', 31, 12/)	WIRE0449
		WRITE/6.79)	STRE0450
			UTDUALET
		WAITE (6,00) AL, ELU, TLU	#1850451
		RL=RLO	WIRE0452
		┲┎╼╤┎᠐	WIREOWS3
			UT D 000 E 0
		20 HC=ZEROC	MINEU434
		SUNS≠2 EROC	WIRE0455
		DO 88 J=1.NLO	WIRE0456
		DENN/C 071 VT WT MT	UT D D A# 67
		READ (3, 67) A1, E1, 11	FIRE0457
	-87	FORMAT (3 (E 10 . 3 , 10 X))	WIRE0458
		WRITE(6,80) XI.EI.TI	WIRE0459
		YD_YT	UTPPORAO
			WIN20400
		EP=EI	WIRE0461
		TP=TI	WIRE0462
			WT BROUG 1
			#1 (LC040)
		AI = (EP - EL) / ID	WIRE0464
		BI = (BL + X P - PP + XL) / XD	WIRE0465
		NT = (PP - PT) / (PADEGAYD)	WT REQUSE
			17 BB0467
		CI = (TA + AP - TP + AL) / (RADEG + AD)	WIREU40/
		NH=NI-BETA	WIRE0468
		NP=NI+BETA	WIRE0469
			UT 0 P A # 70
			WIREV470
		2AUC+2AUC+62CT+62+ (UT+66RT+R1(XT ⁴ X6 ⁴ N4) +4E+EM8T+R1(XT ⁴ X6 ⁴ N5)	MIKEO4/1
		1+BI+EPBL+E2(XL,XP,NH)+BI+ENBL+E2(XL,XP,NP))	WIRE0472
		SUNSESINS-XIPPSPRICT # (NY *EDRIFE1 (YI. YD. NN) - NT+ENRIFE1 (YI. YD. ND)	WIREC474
		CIRTANNIANDIN TO UNCOLOUR LIVE DI MARALINI, LE DUDA DI (RAFRIJUL)	27000170
		1+01+EP6L+E2(#L, #P, NA) - B1+ENBL+E2(#L, #P, NP) }	WEREU474
		XL=XP	WIRE0475
		PL=EP	WIRE0476
	9.9		UTOPON 77
	00		W1850477
		A 1 (T)=20HC-RTOC	ATKE04.48
		V2 (1) =SUNS-BLOS	W1RE0479
r			STRROUAO
ř		CANDING RUP CANADITATION TAL AND TA THE STRUCTURE STRUCTURE	01000000
C		CONFULE THE CONTRIBUTION DUE TO THE THANSVERSE ELECTRIC FIELD	WIKEU481
С		AT X=0 FOR EACH WIRE	WIRE0482
С			WIREOWAR
•		VI - 7990	UT000000
			WINEV484
		WRITE(6,89) I	WIRE0485
	89	FORMAT(// TRANSVERSE ELECTRIC FIELD AT N=0 FOR WIRE . 31.12/1	W1820486
			ETDB0400
		READ (3,03) BLV, BEIV, TAV	WINEU48/
		MKTIE(0,/3)	WIRE0438

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```
WRITE(6,80) IL, EETO, TTO
                                                                                WIRE0489
                                                                                WIREO490
      EL=EETO
      TL=TT0
                                                                                WIRE0491
                                                                                WIR20492
      SUN0=ZEROC
                                                                                WIRE0493
      DO 91 J=1, NTO
      READ (5,90) XI,81,TI
                                                                                WIRBO494
                                                                                WIRE0495
   90 FORMAT (3 (E10.3, 10X))
      WRITE(6,80) XI,FI,TI
                                                                                WIRE0496
                                                                                WIRE0497
      XP=XI
      BP=BI
                                                                                WIRE0498
      TP=TI
                                                                                WIRE0499
                                                                                WIRE0500
      XD=XP-XL
      MI=(EP-EL) /XD
                                                                                WIRE0501
      BI= (EL*XP-BP#XL) /XD
                                                                                WIRE0502
      NI = (TP-TL) / (RADEG*XD)
CI = (TL*XP-TP+XL) / (RADEG*ID)
                                                                                WIRE0503
                                                                                WIRE0504
                                                                                WIRE0505
      EJCI=CDEXP(XJ+CI)
      SUHO=SUSO+EJCI+(HI+E1(XL,XP,NI)+BI+E2(XL,XP,HI))
                                                                                WIRE0506
                                                                                WIRE0507
      IL=IP
      EL=EP
                                                                                WIRE0508
                                                                                WIRE0509
   91 TL=TP
      ETO(I) =SUHO
                                                                                #TRE0510
                                                                                WIRE0511
С
      CONPUTE THE CONTRIBUTION DUE TO THE TRANSVERSE ELECTRIC FIELD
                                                                                WIRE0512
С
С
       AT X=L FOR EACH WIRE
                                                                                WIREOS13
                                                                                WIPE0514
С
                                                                                WIRBOS15
      XL=ZERO
   WRITE(6,92) I
92 FOBHAT(//' TRANSVERSE ELECTRIC FIELD AT X=L FOB WIRE ',3X,12/)
                                                                                WIRE0516
                                                                                WIREOS17
      READ (5,85) NTL, EETL, TTL
                                                                                WIRE0518
                                                                                WIREO519
      WRITZ (6, 79)
      WRITE(6,80) XL, EETL, TTL
                                                                                WIRE0520
                                                                                WIRE0521
      EL=EETL
                                                                                WIRE0522
      TL=TTL
      SU JL=Z BROC
                                                                                VIRE0523
                                                                                WIRE0524
      DO 94 J=1, NTL
      READ(5,93) XI,EI,TI
                                                                                WIRE0525
   93 PORHAT (3 (810.3, 10X))
                                                                                WIRE0526
                                                                                WIBB0527
       WRITE(6,80) XI,EI,TI
                                                                                WIRE0528
       XP=XI
                                                                                WIRE0529
       EP=ET
       TP=TI
                                                                                WIRE0530
       XD=XP-XL
                                                                                WIRE0531
       RI=(EP-EL)/XD
                                                                                WIRE0532
       BT=(EL+IP-EP+XL)/XD
                                                                                WIRE0533
       NI= (TP-TL) / (RADEG*ID)
                                                                                VIRE0534
       CI = (TL + XP - TP + ...) / (RADEG + XD)
                                                                                WIRRO535
       BJCI=COEXP (XJ+CI)
                                                                                VIRE0536
       SUHL=SUHL+EJCI+(HJ+E!(XL,XP,NI)+BI+E2(XL,XP,NI))
                                                                                WIRE0537
                                                                                WIRE0538
       XL=XP
                                                                                #TRR0539
       EL = EP
   94 TL=TP
                                                                                WIRE0540
       ETL(I) = SUNL
                                                                                WIRE0541
                                                                                WIRE0542
   95 CONTINUE
                                                                                WIRE0543
С
       COMPUTE THE TERMINAL COBRENTS
                                                                                WIRE0544
С
С
                                                                                WIRE0545
Ċ
                                                                                WIRE0546
       FORM THE EQUATIONS
                                                                                WIRE0547
С
    96 IF (LSO. NQ. 12. OR. LSO. EQ. 22) GO TO 100
                                                                                WIRE0548
                                                                                WIRE0549
       DO 98 I=1, N
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		SUHO=ZEROC	
		SURL=2 BROC	WIRE0550
		DO 97 J≠1,N	WIRE0551
		A(I,J) = XJ + DS + B2(I,J)	WIRE0552
		SUNO=SUNO+N3 (I, J) + V2 (J)	WIRE0553
	97	SUBL=SUBL+B3 (I, J) + ETO (J)	WIRE0554
		V1(I) = V1(I) - ETL(I)	WIRE0555
		$H_1(I,I) = SUH0$	WIRE0556
		ETL(I) = SUML	WIRE0557
	98	$A(\mathbf{I},\mathbf{I}) = A(\mathbf{I},\mathbf{I}) + DC + (\mathbf{Y})(\mathbf{I},\mathbf{I}) + \mathbf{Y} + \mathbf{Y} + \mathbf{I} + \mathbf{Y}$	WIRE0558
		DO 99 $I = 1.N$	WIRE0559
		SUN0=ONEC	WIRE0560
		SUNL=ONEC	WIRE0561
		IF (LSO, E0, 21) SHAD=VI (T T)	WIRE0562
		IF (LSO, EO. 11) SUNLEYL (T T)	WIRE0563
	99	$B(I) = S(H) 0 \neq V(I) + X_1 +$	WIRE0564
		GO TO 107	WIRE0565
	100	DO 102 I=1.N	WIRE0566
		SUN0=ZEROC	WIRE0567
		SUNL=ZEROC	WIRE0568
		DO $101 J = 1.N$	WIRE0569
		$A(T_{J}J) = XJ = DS = H2(T_{J}) + DC = (VO(T_{J}) + DC = (VO(T_{J})))$	WIRE0570
		$SUM0 = SUM0 + M3 (T_1) + M2 (T_1) + TL(1, J) + TL(1, J))$	WIRE0571
	101		VIREO572
			WIRE0573
			WIREOS74
	102		WIRPOS75
	•••		WIRE0576
			WIRE0577
			WIRE0578
			WIRE0579
			WIRE0580
			WIRE0581
	103		WIRE0582
			WIREOS83
		CO. TO 104	WTRE0584
	104		WIRE0585
			STRE0586
			WTBE0587
			WIREOS88
	105		WIRE0589
			WIRE0590
	106	CONTINUE CONTINUE (1, 1) + DC = SUNL + XJ + DS + ETL (1)	WIRP0591
С			WIRE0592
č			WIRE0593
č		SOULD THE EQUATIONS	WIRE0594
Ũ	107		WTRE0595
		(abb bb control (a, a, n, b, 1, N, 0, WA, IBR)	WTRE0596
		408-159-120 WDT#P/6 400, m	WTRE0597
	108	FORMAT(184 1 Paramental data a	WTRE0598
		TE (THE WE HERD CONCECTED (HERTZ) - 1, 1PE 16.9, ///)	WTRE0599
		AF (1ER. HE, I) GO TO) 10 PDTHEAF 100	WIRFOGOO
	109		WT RF0601
		Co mo 121	WTRE0602
	110	90 10 121 97797/6 1119	WIREOGON
	111	PORNAT/16V ERTERE ON LIGHT CONTRACTOR	WTREOGOU
	••••	TTHANDEL	WTRR0605
C	"	Lun (Anro) *, 4X, * ILA (DEGREES) *///}	WIREOGOG
č			WTRP0607
č		CONFULD AND PRINT THE TERMINAL CURRENTS	WTRE0608
č		DO 114 Tel N	WTREGAGO
			WIRE0610

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	IF (LSO. EQ. 11.08, LSO. EQ. 21) GO TO 113	WIRE0611
	SUB0=ZBROC	WIRE0612
	DO 112 J=1,K	WIREO613
112	SUNO=SUNO+YO(I,J) +B(J)	WIRBO614
	WA(I)=SUHO	WIREO615
	GO TO 114	WIRE0616
113	WA(I) = YO(I, I) * B(I)	WIRE0617
114	CONTINUE	WIRE0618
	DO 120 I=1,N	WIRE0619
	IF (LSO.EQ.21.0B.LSO.EQ.22) GO TO 116	WIRE0620
	IO=B(I)	WIRE0621
	SUH0=ZEROC	WIRE0622
	DO 115 J=1,N	WIRE0623
115	SUHO=SUHO+N3 (I, J) +WA (J)	WIRE0624
	IL=-XJ*(H1(I,I)+DS*ETL(I))+DC*B(I)+XJ*DS*SUH0	WIRE0625
	GO TO 118	WIRE0626
116	IO=WA(I)	WIRE0627
	SUR0=ZBROC	WIRE0628
	DO 117 J=1,N	WIRE0629
117	SUH0=SUH0+H3(I,J) +B(J)	WIRE0630
	IL=-XJ*(H1(I,I)+DS*ETL(I))+DC*WA(I)+XJ*DS*SUNO	WIRE0631
118	IOM=CDABS(IO)	WIRE0632
	TLM=CDABS(IL)	WIRE0633
	IOR=DREAL(IO)	WIRBOG 34
	IOI=DIHAG(IO)	WIRB0635
	ILR=DREAL(IL)	WIREO636
	ILI=DINAG(IL)	WIRE0637
	IF (IOR.EQ.ZERO.AND.IOI.EQ.ZERO) IOR=ONE	WIRE0638
	IF (ILR, EQ. ZERO, AND. ILI. EQ. 2ERO) ILR=ONE	WIREO639
	IOA=DATAN2 (IOI, IOR) + RADEG	WIRE0640
	ILA=DATAN2 (ILI,ILR) + RADEG	WIRE0641
	WRITE(6,119) I, ION, IOA, ILN, ILA	WIRE0642
119	PORNAT (18X, 12, 7X, 1PE 10. 3, 4X, 1PE 10. 3, 9X, 1PE 10. 3, 4X, 1PE 10. 3/)	WIRE0643
120	CONTINUE	WIRE0644
	GO TO 66	WIRE0645
121	STOP	WIRE0646
	RND	WIRE0647

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Delata 0062				
Cond				
Card		Double Precisio	<u>on</u>	Single Precision
0064		REAL *8		REAL
0066		COMPLEX *16		'`OMPI EV
0071-0072	Change all	D's	to	JOIN LEA
0073		0.00	20	E's
0074		0.00		0.E0
0075		1.D0		• E0
0075		2.D0		2.EO
0076		DCMPLX(1.D0,0.D	0)	CMPLX (1, EQ. (1.) ON
0077		DCMPLX (0.D0,0.D	0)	
0078		DCIPLX(0,D0,1,D	0)	CITE LA (0. E0, 0. E0)
0079		Πάπανι	.,	CMPLX(0.E0,1.E0)
0150		DATAN		ATAN
0161		DSQRT		SQRT
0101		DLOC		ALOG
0163		DLOG		ALOG
0165		DLOG		41.00
0182		DLOG		ALUG
0188				ALOG
0194		DLUG		ALOG
0105		DLOG		ALOG
0195		DCOS		COS
0195		DCOS		COS
0293		DSQRT		CODT
0312		DCOS		ουκι
0313				COS
		0005		COS

APPENDIX B-1

Conversion of WIRE to Single Precision

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APPENDIX B-1 (continued)

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Card	Double Precision	Single Precision
0314	DCOS	COS
0315	DSIN	SIN
0316	DSIN	SIN
0317	DSIN	SIN
0332	DSIN	SIN
0333	DCOS	COS
0345	CDEXP	CEXP
0348	CDEXP	CEXP
0349	CDEXP	CEXP
0361	CDEXP	CEXP
0362	CDEXP	CEXP
0363	CDEXP	CEXP
0378	DSIN	SIN
0379	CDEXP	CEXP
0390	CDEXP	CEXP
0391	CDEXP	CEXP
0427	CEDXP	CEXP
0470	CDEXP	CEXP
0505	CDEXP	CEXP
0536	CDEXP	CEXP
0632	CDABS	CABS
0633	CDAES	CABS
0634	DREAL	REAL

APPENDIX B-1 (continued)

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1944-40X

Card	Double Precision	Single Precision
0635	DIMAG	AIMAG
0636	DREAL	REAL
0637	DIMAG	AIMAG
0640	DATAN2	ATAN2
0641	DATAN 2	ATAN 2





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ZEROC	= 0.+j0.
XJ	= 0.+j1.
V(velocity of light in free space)	= 2.997925 x 10 ⁸ m/sec
PI	= π
RADEG(conversion of radians to degrees)	= 180./π

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Read and print:	
Structure type (1,2,3)	= TYPE
Load Structure option (11,12,21,22)	= LSO
Field Specification option (1,2)	= FSO
Number of wires (n)	- N
Relative permittivity of medium (ϵ_r)	= ER
Relative permeability of medium (μ_r)	= MUR
Line length (1)	= L
TYPE = 1;	
Radius of reference wire, ^r w0,	= RWO
TYPE = 3;	
Interior radius of cylindrical shield	= RS

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APPENDIX C

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Function Subprograms

E1, E2

Program Listings

COMPLEX FUNCTION E1+16 (A, B, X) INPLICIT REAL*8 (A-H, 0-Z) COMPLEX# 16 XJ, ONEC DATA THREE/3.DO/,PZ1/1.D-2/,TEN/10.DO/ CONMON XJ, ZERO, TWO, ONE, ONEC 82=B*B X2=X*X XB=X*B $\chi \chi = \chi * \chi$ BPA=B+A XBPA2=X*BPA/TWO BN A=B-A XBHA2=X+BHA/THO IF (IBPA2.EQ. ZERO) GO TO 1 SBPA=DSIN(XBPA2)/XBPA2 GO TO 2 1 SBPA=ONE 2 IF (XBMA2.EQ. ZERO) GO TO 3 SBEA=DSIN (XBNA2) /XBNA2 GO TO 4 3 SBMA=ONE 4 IF (XB. EQ. ZERO) GO TO 5 SB=DSIN(XB)/XB GO TO 6 5 SB=ONE 6 IF (XA. EQ. ZERO) GO TO 7 SA=DSIN(XA)/XA GO TO 8 7 SA=ONE 8 XR=-SBPA+SBNA+ (B2-A2) /TWO+ B2+SB-A2+SA IF (X. EQ. ZERO) GO TO 13 IF (DABS (XA). LE. P21) GO TO 9 XIA=A*(DCOS(XA)-SA)/XGO TO 10 9 XIA=-XA+A2+ ((ONE-XA+XA/TEN) /THREE) 10 IF (DABS (XB) . LE. PZ1) GO TO 11 IIB=B+ (DCOS(IB)-SB)/I GO TO 12 11 XIB=-XB+B2+((ONE-XB+XB/TEN)/THREE) 12 XI=XIA-XIB GO TO 14 13 XI=ZERO 14 Bi=XR+XJ+XI RETURN END

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FNE10001 FNE10002 FNE10003 FNE10004 FNE10005 FNE10006 FNE10007 FNE10008 FNE10009 FNE10010 FNE10011 FNE10012 FNE10013 PNE10014 **FNE10015** FNE10016 **FNE10017** FNE10018 FNE10019 FNE10020 FNE10021 FNE10022 FNE10023 FNE10024 FNE10025 FNE10026 FNE10027 FNE10028 FNE10029 FNE10030 FNE10031 FNE10032 FNE10033 FNE10034 FNE10035 FNE10036 FNE10037 FNE10038 FNE10039 FNE10040 FNE10041 PNE10042 FNE10043 FNE10044 PNE10045

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APPENDIX C-1

Conversion of El to Single Precision

`Delete Card 0002

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International version

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001		E1*16		E1
0003		COMPLEX*16		COMPLEX
0004	Change all	D's	to	E's
0015		DSIN		SIN
0019		DSIN		SIN
0023		DSIN		SIN
0027		DSIN		SIN
0032		DABS		ABS
0033		DCOS		COS
0036		DABS		ABS
0037		DCOS		cos

	COMPLEX FUNCTION E2+ 16 (A, B, X)	FNE20001
	INPLICIT REAL+8 (A-H, 0-Z)	FNE20002
	COMPLEX*16 XJ, ONEC	FNE20003
	CONNON 1J, ZERO, TWO, ONE, ONEC	F8220004
	DIF=B-A	FHE20005
	FA=X+DIF/TWO	FNE20006
	$PB=X*(B+\lambda)/TWO$	FNE20007
	IP (PA. EQ.ZERO) GO TO 1	FNE20008
	E2=DIF+ (DSIN (FA) /FA) +CDEXP (XJ+FB)	FNE20009
	GO TO 2	FNE20010
1	E2=DIF+ONEC	FNE20011
2	CONTINUE	FNE20012
	RETURN	FNE20013
	END	FKE20014

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APPENDIX C-2

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Conversion of E2 to Single Precision

Delete Card 0002

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0001	E2*16	E2
0003	COMPLEX*16	COMPLEX
0009	DSIN	SIN
0009	CDEXP	CEXP

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