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BASIC EMC TECHNOLOGY ADVANCEMENT FOR C³ SYSTEMS - SHIELD, A Digital Computer Program for Computing Crosstalk Between Shielded Cables

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This report contains the description and verification of a digital computer program, SHIELD, to be used in the prediction of crosstalk in transmission lines consisting of unshielded wires and/or shielded cables. The line may be above a ground plane (Type 1) or within an overall, circular, cylindrical shield which may be solid or braided and a wire (the shielded wire) located concentrically on the axis of the shield. All wires may be stranded and all conductors are treated as imperfect conductors; that is, →

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) their per-unit-length impedances are nonzero. Through-braid coupling for braided shields as well as diffusion for both types are included in the model. The shielded cables may have exposed sections at either end (pigtail sections) in which the shielded wire is not covered by the shield Over these pigtail sections, a pigtail wire, parallel to the shielded wire, connects the shield to the reference conductor at that end via either a short circuit or an open circuit. These pigtail sections are included in the representation to simulate the common practice of terminating a shielded cable in a connector via these pigtail wires. The pigtail sections may be of different lengths. The program is written in FORTRAN IV and should be implementable on a wide range of digital computers.

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PREFACE

The author of this report is Clayton R. Paul. He received the B.S. degree from The Citadel, Charleston, S.C., in 1963, the M.S. degree from Georgia Institute of Technology, Atlanta, in 1964, and the Ph.D. degree from Purdue University, Lafayette, IN., in 1970, all in electrical engineering.

From 1964 to 1965, he served as an Instructor on the faculty of Georgia Institute of Technology and from 1970 to 1971 held a Postdoctoral Fellowship with the Electromagnetic Compatibility Branch, Rome Air Development Center, Griffiss AFB, N.Y. He is currently a Professor of Electrical Engineering at the University of Kentucky, Lexington.

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I. Introduction

Shielded cables have been used extensively on aircraft, ground and space-missile systems to reduce the electromagnetic coupling (crosstalk) between electrical equipments which are interconnected by wires. The wires which interconnect these electrical and electronic devices are generally routed in densely-packed, cable bundles. The unintentional electromagnetic coupling or crosstalk between these wires may be of sufficient magnitude to degrade the performance of the equipments which the wires interconnect. In order to reduce this level of crosstalk, shielded cables and twisted pairs of wires have been employed.

In an earlier report [1], the prediction of crosstalk to braided-shield cables was investigated. The braided-shield cable consists of a circular, cylindrical shield which is composed of belts of wires, interwoven to provide flexibility and an interior wire (the shielded wire) located on the axis of the shield as shown in Fig. 1-1. The interior wire or shielded wire is of radius r_w and the shield has radius r_s. The shield thickness, t_s, is approximately equal to the diameter of the wires making up the braid which have radius r_b, i.e., $t_s \cong 2r_b$. The shielded cable usually has an overall, insulating jacket of thickness t_j, and the shield is woven in B belts of wires with a weave angle of Θ_w as shown in Fig. 1-1. Each belt contains W wires. If the length of the shield is denoted by $\mathcal{L}_s$, then each braid wire is of length $\mathcal{L}_s/\cos\Theta_w$. The medium internal to the shield and surrounding the interior, shielded wire is a dielectric with permittivity $\varepsilon = \varepsilon_r\varepsilon_v$ and permeability $\mu = \mu_v$ where the permittivity and permeability of free space are denoted by ε_v and μ_v, respectively.

In terminating a braided-shield cable, for example, at a connector, the

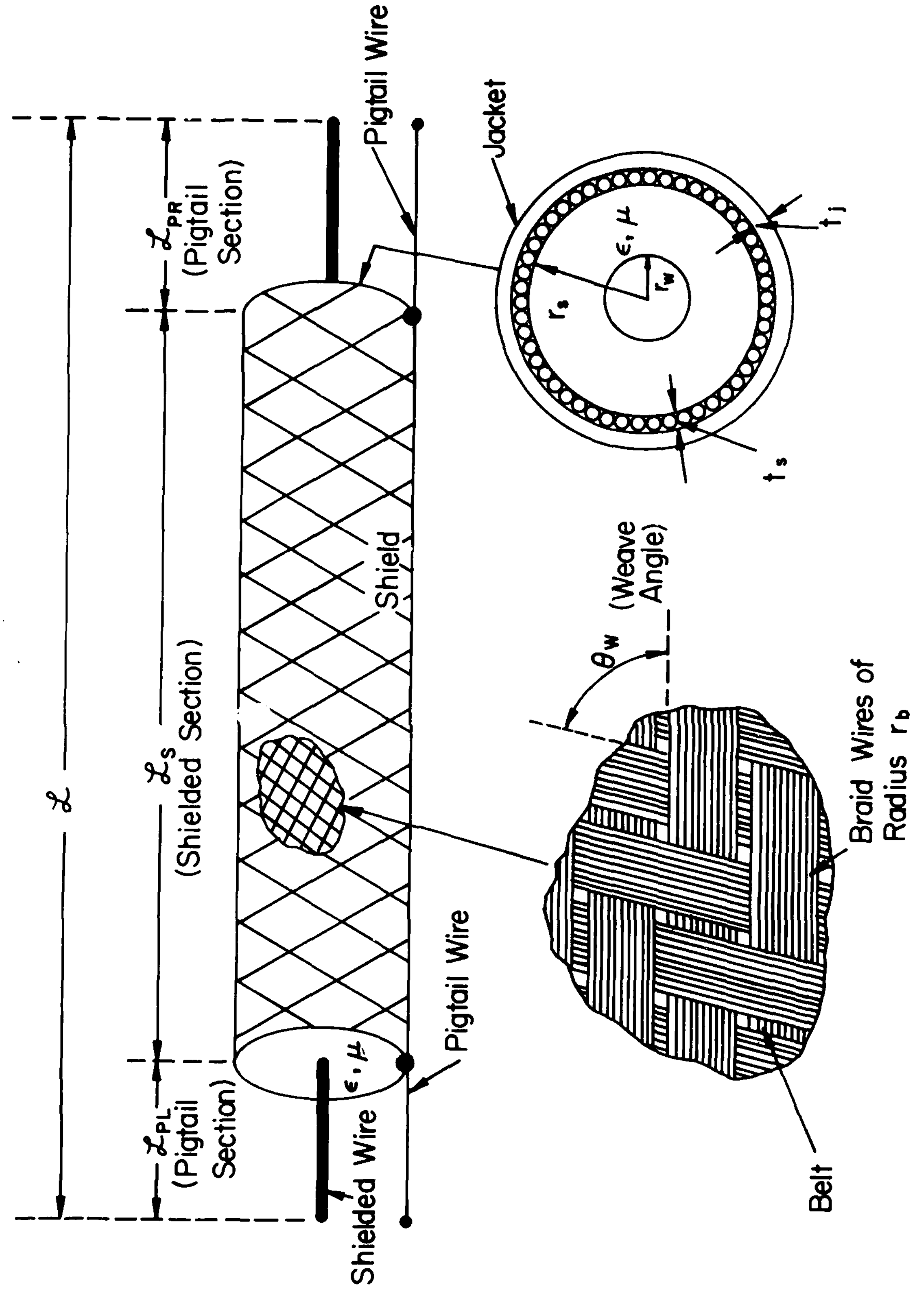


Figure 1-1. Braided-shield construction.

braid is often stripped back exposing the interior, shielded wire as shown in Fig. 1-1. The braid is terminated (usually to a ground plane such as an aircraft structural skin) via another wire which will be referred to as the pigtail wire. These exposed terminal sections will be referred to as pigtails throughout this report although this use of the term is not standard. The term pigtail is sometimes used elsewhere to denote the pigtail wire. The length of the left pigtail section will be denoted by $\mathcal{L}_{pL}$ and that of the right section will be denoted by $\mathcal{L}_{pR}$. The total length of the cable is denoted as $\mathcal{L} = \mathcal{L}_{pL} + \mathcal{L}_{s} + \mathcal{L}_{pR}$.

When braided shield cables are terminated in connectors in this fashion, the shielded wire is directly exposed over the pigtail sections to other wires in the cable bundle which are also terminated at the connector as shown in Fig. 1-2. If it is desired to carry a shield connection through the connector, a separate wire, the pigtail wire, connects the shield braid to an additional connector pin. To avoid bunching of these shields at the connector, the pigtail sections at a connector are generally of different lengths. The various design handbooks [4,5,6] seem to recommend against using pigtail sections. It appears to be common nevertheless [7,8]. In fact the author has observed pigtail sections in excess of 6 inches.

It was shown previously [1,2] that the coupling over the pigtail sections may constitute the dominant coupling mechanism to the shielded wire. Even though the total length of the pigtail sections, $\mathcal{L}_{pL} + \mathcal{L}_{pR}$, may constitute only a minor fraction of the total cable length, it was shown in [1,2] that, depending on the values of the cable termination impedances, the contribution to the received voltages at either end of the cable (the voltages of the shielded wires) due to the pigtail sections can be larger than the contribution

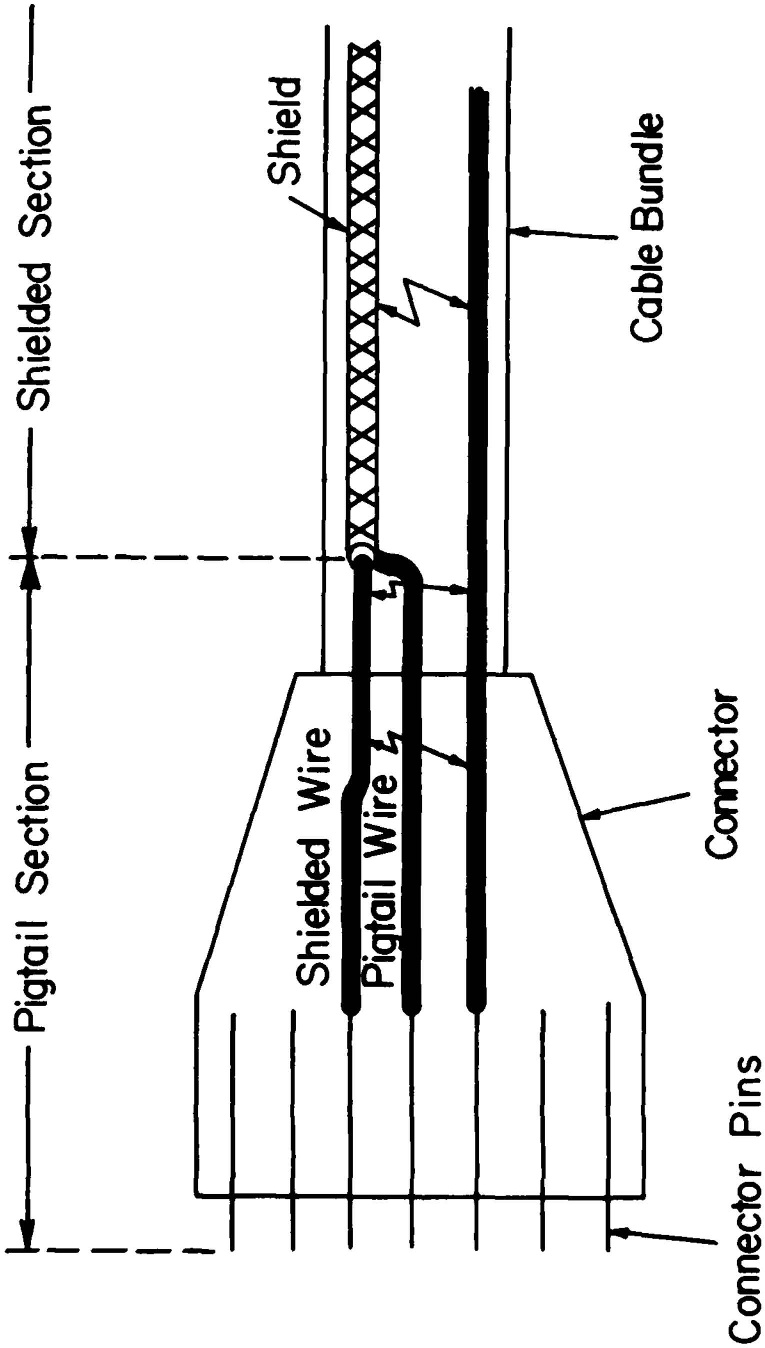


Figure 1-2. Termination of braided-shield cables in connectors.

over the (much longer) shielded section. In this situation, the shield simply serves to reduce the exposed length of the interior wire ($\mathcal{L}_{pL} + \mathcal{L}_{pR}$) from what it would be if no shield were present ($\mathcal{L}$). Thus the shield still provides a reduction in crosstalk. However, it was shown in [1,2] that if the pigtail sections were eliminated, one could realize an additional reduction in crosstalk of as much as 30dB (over certain frequency ranges). Thus the effectiveness of the shield in reducing crosstalk can be substantially reduced by the pigtail sections.

An additional result shown in [1,3] was that the crosstalk to or from a braided-shield cable including the effects of pigtail sections could be predicted quite accurately with the multiconductor transmission line model (MTL) whose basic features are described in [9]. Certain other features of the coupling which are distributed parameter in nature could not be predicted with lumped circuit models. For example, it was shown in [1,2] that the coupling to a shielded cable in which only one end is grounded depended, in some cases, very strongly on which end of the shield was grounded. This is clearly a distributed parameter phenomenon, and the MTL model predicted this result quite accurately. In addition, it was shown in [2] that the coupling to a shielded wire may depend quite strongly on the orientation of the pigtail wires. Simple lumped models failed to predict these effects, whereas the MTL model predicted these results quite accurately.

In order to describe the coupling through cable shields we first consider a cable having a solid shield. The coupling from an exterior field to the interior, shielded wire for solid-shield cables is described by a surface transfer impedance, z_T, per-unit-of cable length. For an infinitely long, solid, conducting cylinder, suppose the cylinder carries a total current I directed in the axial (x) direction where $I = I_{in} + I_{out}$. The return path for I_{in} is within the cylindrical surface while the return path for I_{out} is outside the surface. The conducting cylinder has finite conductivity σ and therefore the current I flowing along the cylinder will induce electric fields on the inner and outer surfaces of the cylinder, E_{in} and E_{out}, respectively, which are directed in the axial direction of the cylinder. The currents and induced electric fields may be related as [10-13, 19, 22]

$$\begin{bmatrix} E_{in} \\ E_{out} \end{bmatrix} = \begin{bmatrix} z_{ii} & z_{io} \\ z_{oi} & z_{oo} \end{bmatrix} \begin{bmatrix} I_{in} \\ I_{out} \end{bmatrix} \quad \text{V/m} \tag{1-1}$$

The terms z_{ii} and z_{oo} may be thought of as per-unit-length self impedances of the surfaces:

$$z_{ii} = \left. \frac{E_{in}}{I_{in}} \right|_{I_{out} = 0} \quad \Omega/\text{m} \tag{1-2a}$$

$$z_{oo} = \left. \frac{E_{out}}{I_{out}} \right|_{I_{in} = 0} \quad \Omega/\text{m} \tag{1-2b}$$

whereas the terms z_{io} and z_{oi} are called surface transfer impedances (per-unit-length):

$$z_{io} = \left. \frac{E_{in}}{I_{out}} \right|_{I_{in} = 0} \quad \Omega/\text{m} \tag{1-3a}$$

$$z_{oi} = \left. \frac{E_{out}}{I_{in}} \right|_{I_{out} = 0} \quad \Omega/\text{m} \tag{1-3b}$$

These surface transfer impedances relate the current on one surface of the cylinder to the induced field on the other surface.

The two surface transfer impedances z_{io} and z_{oi} will be assumed to be equal and will be designated as z_T, i.e.,

$$z_T = z_{io} = z_{oi} \tag{1-4a}$$

The self-impedances of the shield, z_{ii} and z_{oo} will also be taken to be the same and designated as z_S, i.e.,

$$z_S \cong z_{ii} \cong z_{oo} \tag{1-4b}$$

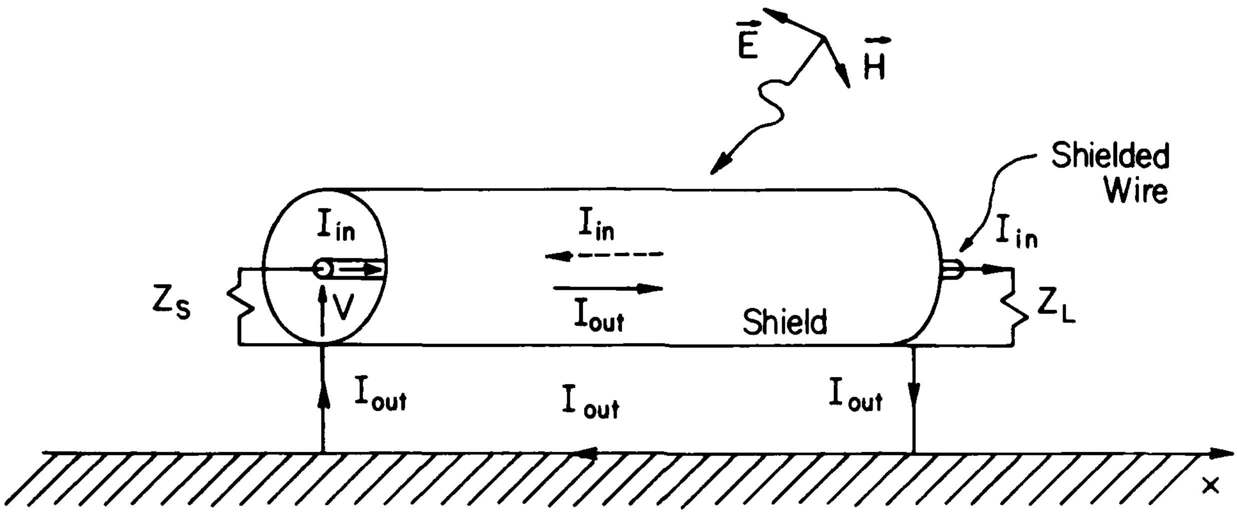
Certainly for cylinders with wall thicknesses which are sufficiently small, these will be reasonable approximations. Thus (1-1) becomes

$$\begin{bmatrix} E_{in} \\ E_{out} \end{bmatrix} = \begin{bmatrix} z_S & z_T \\ z_T & z_S \end{bmatrix} \begin{bmatrix} I_{in} \\ I_{out} \end{bmatrix} \tag{1-5}$$

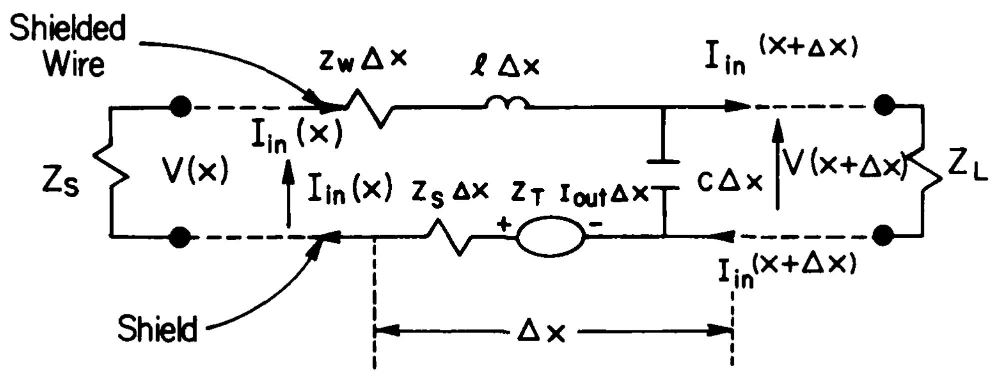
The surface transfer impedance accounts for skin effect - the tendency for a current to concentrate on a conductor surface nearest its source. At D-C, any current flowing in the shield will tend to be uniformly distributed over the shield cross section. As the frequency is increased the current tends to concentrate towards the shield surfaces. Thus for increasing frequencies less current diffuses through the wall to induce an electric field on the opposite surface. In the limit as the frequency is increased without bound there is perfect isolation between the inner and outer walls of the shield. If the frequency is sufficiently small so that the shield thickness is less than a few skin depths, the surface transfer impedance is approximately equal to the impedance of the shield. In fact, the two should converge as the frequency is reduced to zero. We will often refer to this surface transfer impedance, z_T, for solid shields as the diffusion impedance and denote it as $z_d = z_T$ for the above reasons.

The surface transfer impedance represents the coupling of some field external to the cylinder to the field internal to the cylinder and occurs via diffusion through the finitely conducting shield. This surface impedance is employed to predict the coupling from some field incident on a coaxial cable to the loads connected to the end points of the coaxial cable in the following manner [19]. As an example, consider the coaxial cable above the ground plane shown in Fig. 1-3(a). The coaxial cable consists of a conducting cylinder and a concentrically-located, conducting wire. An incident field, such as a uniform plane wave, illuminates the cable and induces a current, I_{out}, flowing along the shield and returning through the ground plane. For the purposes of computing this induced current, I_{out}, it is universally assumed that the interior of the shield and, in particular, I_{in} have no effect on the external circuit [19]. In other words, I_{out} is traditionally calculated as simply the current induced on an isolated cylinder above ground. Thus we assume a unilateral effect - outside to inside - to simplify the calculations. Then the effect of this induced current, I_{out}, and consequently the incident field, on the internal structure is manifested as a per-unit-length voltage source in the cable interior equal to $z_T \, I_{out}$ (V/m). The equivalent circuit representing a small, Δx section of the shield and interior, shielded wire is shown in Fig. 1-3(b).

The per-unit-length impedance of the interior wire is represented by z_w and the per-unit-length inductance and capacitance of this Δx section of the line are represented by ℓ and c, respectively. The current I_{in} produces a



(a)



(b)

Figure 1-3. Field-to-wire coupling involving shielded cables.

voltage drop z_s Δx I_{in} along the interior surface of the shield as indicated by (1-1) and (1-2a), and the effect of the external shield current, I_{out}, induced by the incident field is represented by a voltage source z_T I_{out} Δx as indicated by (1-1) and (1-3a).

From the equivalent circuit in Fig. 1-3(b), we may derive the transmission line equations as [9]

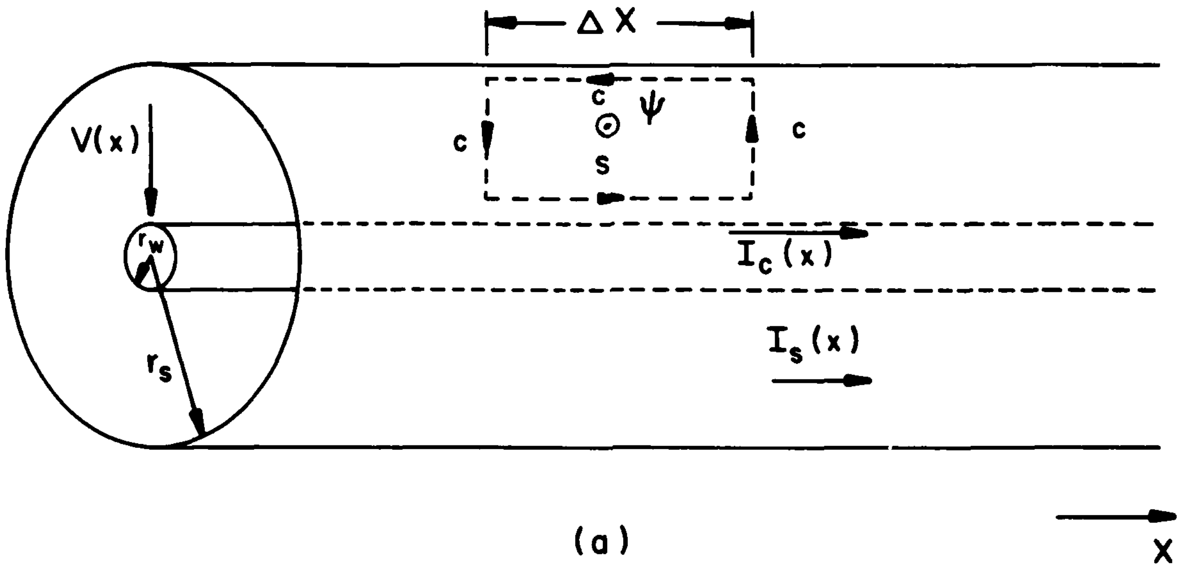
$$\frac{dV(x)}{dx} = -(z_w + z_s + j\omega\ell)\, I_{in}(x) + z_T\, I_{out}(x) \qquad (1\text{-}6a)$$

$$\frac{dI_{in}(x)}{dx} = -j\omega c\, V(x) \qquad (1\text{-}6b)$$

Note that the effect of the incident field appears in these transmission line equations as a driving term, $z_T I_{out}$.

This is an example of the use of the surface transfer impedance for solid, cylindrical shields. For braided shields, additional coupling occurs via the small holes in the shield introduced by the overlapping, wire braid. This construction of the shield braid introduces small, diamond-shaped holes between the belts of wires. These holes allow other coupling mechanisms to occur between the outside environment and the interior, shielded wire which were not present for a solid shield. For the solid shield, the coupling from the exterior to the interior occurred only by diffusion through the metal. For the braided shield, additional inductive and capacitive coupling occur via the holes in the shield as discussed by Latham [15,16] and Vance [17].

Latham provided the following development. Suppose the braided shield and interior wire are perfectly conducting. Consider a small Δx section of the cable as shown in Fig. 1-4. Select a planar surface of length Δx between the interior wire and the shield as shown in Fig. 1-4(a). Faraday's law



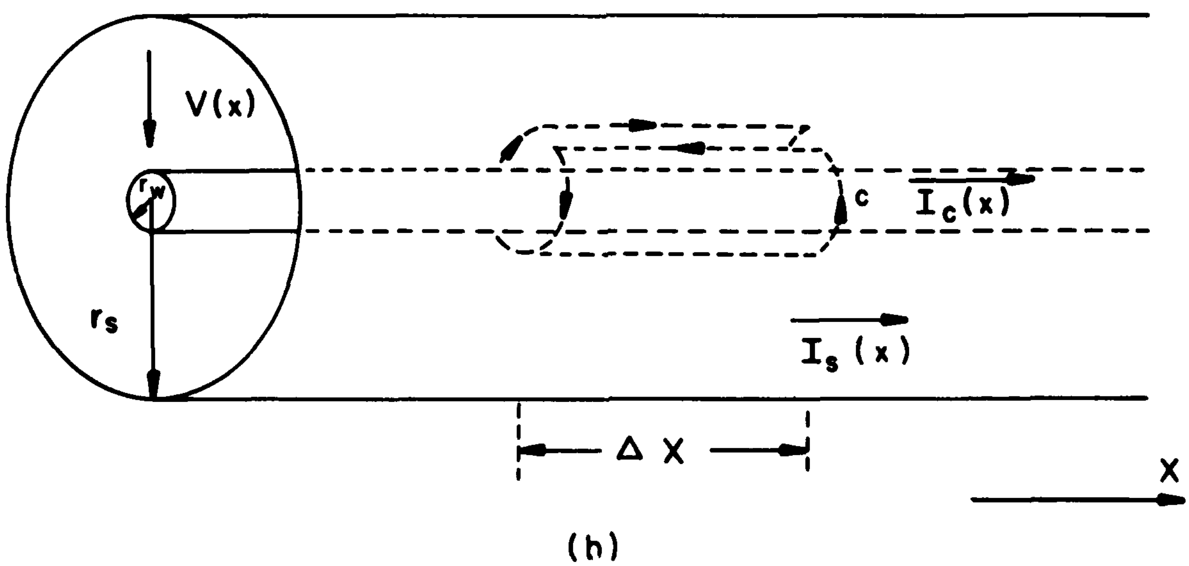


Figure 1-4. Surfaces and contours for the derivation of the transmission-line equations.

written around this contour is

$$\oint_c \vec{E} \cdot \vec{d\ell} = - j\omega\mu \int_s \vec{H} \cdot \vec{ds} \tag{1-7}$$

$$= -j\omega\psi$$

Write the flux through the surface as

$$\psi = \ell \; \Delta x \; I_c - \ell_T \; \Delta x \; I_s \tag{1-8}$$

where I_c is the total current carried by the interior wire and I_s is the total current carried by the shield. Defining the voltage between the interior wire and the shield as

$$V(x) = - \int_{\text{shield}}^{\text{wire}} \vec{E} \cdot \vec{d\ell} \tag{1-9}$$

we obtain

$$V(x + \Delta x) - V(x) = - j\omega(\ell_c \Delta x \; I_c - \ell_T \Delta x \; I_s) \tag{1-10}$$

Dividing (1-10) by Δx and taking the limit as $\Delta x \to 0$ yields

$$\frac{dV(x)}{dx} = - j\omega\ell \; I_c(x) + j\omega\ell_T \; I_s(x) \tag{1-11}$$

and

$$\ell = \frac{\mu}{4\pi} \ell n \left(\frac{r_s}{r_w}\right) \tag{1-12}$$

is the per-unit-length self inductance of the cable where μ is the permeability of the interior medium. The quantity ℓ_T is the per-unit-length transfer inductance which is zero for solid, circular, cylindrical shields which have the interior wire on the axis of the shield. Holes in the shield as well as shields having a conducting direction not along the x axis (such as tape-wound) cause ℓ_T to be nonzero.

Similarly, consider Fig. 1-4(b). A closed surface is constructed around the interior wire. Writing Ampere's law for this surface

$$\oint_c \vec{H} \cdot \vec{d\ell} = j\omega\varepsilon \int_s \vec{E} \cdot \vec{ds} \tag{1-13}$$

we obtain

$$I_c(x + \Delta x) - I_c(x) = j\omega \, Q_c(x) \tag{1-14}$$

where Q_c is the total charge contained on the interior wire over Δx. The charge on the interior wire and on the shield, Q_s, can be related to the voltage as

$$V \, \Delta x = s \, Q_c - s_T \, Q_s \tag{1-15}$$

Solving (1-15) for Q_c and substituting into (1-14) we obtain as $\Delta x \to 0$,

$$\frac{dI_c(x)}{dx} = - j\omega \frac{1}{s} V(x) - j\omega \frac{s_T}{s} Q_s(x) \tag{1-16}$$

For a circular, cylindrical shield

$$s = \frac{1}{2\pi\varepsilon} \ell n \left(\frac{r_s}{r_w}\right) \tag{1-17}$$

The transfer elastance s_T is due to the penetration of the electric field lines through the shield. The terms ℓ_T and s_T are determined for braided shield cables in terms of the magnetic and electric polarizabilities of the holes in the braid [16].

Vance [16] has chosen to include the diffusion term in the voltage change expression for braided shields as was present for solid shields. For a braided shield, Vance assumed that all strands of the braid were connected, electrically, in parallel. For example, if there are B belts of wires, W wires per belt and the braid is woven with a weave angle Θ_w, then the per-unit-length D-C resistance of the braid is

$$r_{DC} = \frac{1}{\pi r_b^2 \sigma B W \cos\Theta_w} \quad \Omega/m \tag{1-18}$$

where r_b is the radius of each strand and σ is the strand conductivity. Vance presumes that this braid impedance is modified with increasing frequency in the same manner as the solid cylinder. Thus the per-unit-length diffusion impedance, z_d, is taken by Vance to be

$$z_d = r_{DC} \frac{\gamma d}{\sinh\gamma d} \quad \Omega/m \tag{1-19}$$

where d is the diameter of the braid wires, $d = 2r_b$, and $\gamma = (1 + j)/\delta$ where $\delta = (\pi f \mu \sigma)^{-1/2}$ is the skin depth. The self impedance of each strand of the braid, z_s, is chosen here to be computed as the impedance of an isolated round wire. The total self impedance of the braid is then chosen as the impedance of all strands in parallel.

Comparing Fig. 1-3 and Fig. 1-4(a) we note that

$$I_c = I_{in} \tag{1-20a}$$

$$I_s = I_{out} - I_{in}$$

or

$$I_{in} = I_c \tag{1-20b}$$

$$I_{out} = I_s + I_c$$

Substituting (1-20b) into (1-6) and adding the transfer inductance and transfer elastance we obtain

$$\frac{dV(x)}{dx} = -(z_w + z_s + j\omega \ell - z_d)\ I_c(x) + (z_d + j\omega \ell_T)\ I_s(x) \quad \text{(1-21a)}$$

$$\frac{dI_c(x)}{dx} = -j\omega c\ V(x) - j\omega c\ s_T\ Q_s(x) \quad \text{(1-21b)}$$

where the diffusion impedance is z_d and the total transfer impedance for the braided shield now becomes

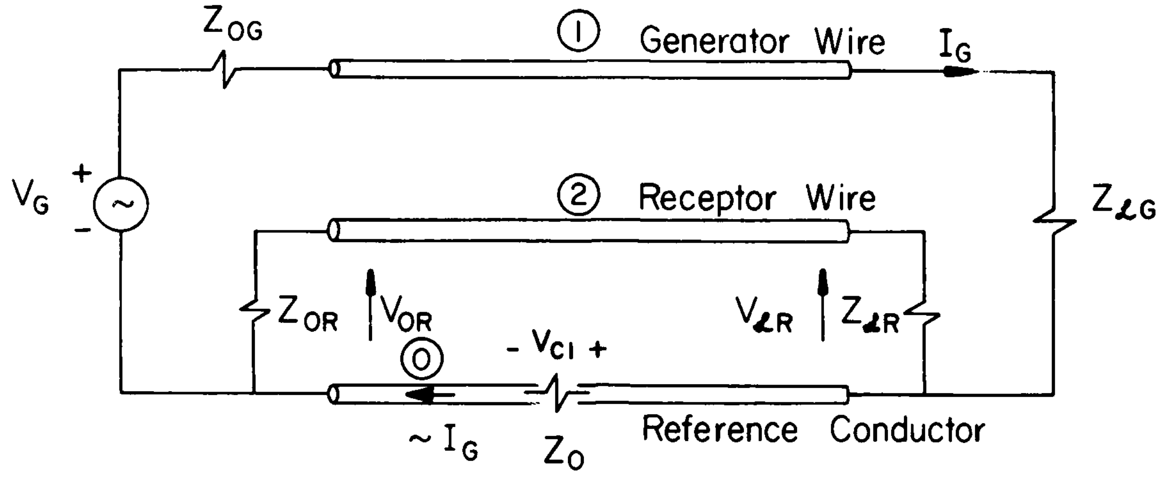
$$z_T = z_d + j\omega \ell_T\ \Omega/m \quad \text{(1-22)}$$

The purpose of this report is to extend the above concepts to multiconductor cables in which the individual wires may be unshielded or shielded with solid or braided shields. The results will be incorporated into a digital computer program, SHIELD, which may be used to predict crosstalk in cables which have shielded wires. A description of the program is given in Section III. A User's Manual is given in Section IV. The shields may have pigtail sections as described previously. The pigtail section lengths need not be the same. Two choices of reference conductor for the line voltages are available. The cables may be over a ground plane or within an overall, circular cylindrical shield.

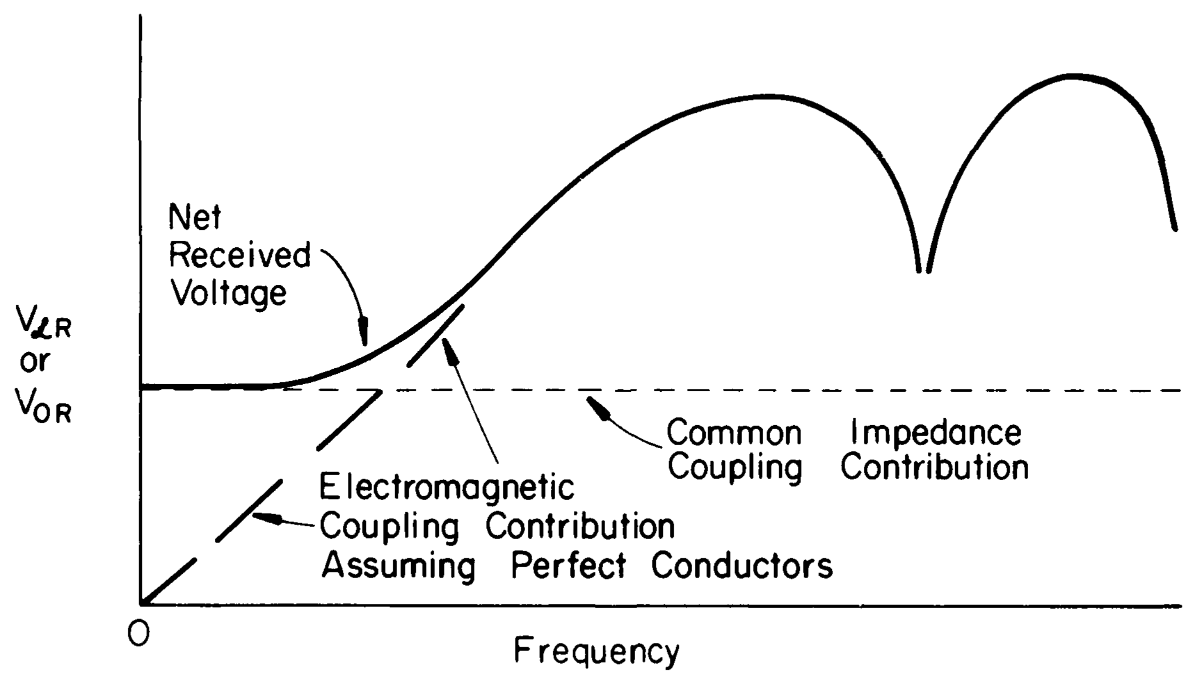
The distributed impedances of all conductors due to their finite conductivities are included in the model. This allows the modeling of common impedance coupling as is illustrated in Fig. 1-5. Consider two wires and a reference conductor shown in Fig. 1-5(a). At a sufficiently small frequency, the current in the generator wire can be computed as

$$I_G \doteq \frac{V_G}{Z_{0G} + Z_{\ell G}} \quad \text{(1-23)}$$

The majority of this current passes through the reference conductor producing a voltage drop across the reference conductor total impedance Z_0, of



(a)



(b)

Figure 1-5. Common impedance coupling.

$$V_C \doteq Z_0 I_G \tag{1-24}$$

This common impedance voltage is then coupled directly to the receptor circuit producing voltages

$$V_{OR} = \frac{Z_{OR}}{Z_{OR} + Z_{\ell R}} V_C \tag{1-25a}$$

$$V_{\ell R} = -\frac{Z_{\ell R}}{Z_{OR} + Z_{\ell R}} V_C \tag{1-25b}$$

These low-frequency voltages produce a "floor" in the low-frequency crosstalk as shown in Fig. 1-5(b).

Each cable shield may be grounded to the reference conductor (via the pigtail wires) at one end, both ends or neither end. The lengths of each pigtail section on each shielded cable may be chosen by the user. For example, a shield may have no pigtail at one end and a pigtail at the other.

In section II, the derivation of the line equations is presented. Comparisons of the code predictions with experimental data are provided in Section V. A listing of the code is given in the Appendix.

II. Derivation of the Line Equations

The basic technique is illustrated in Fig. 2-1. A line is shown for illustration in Fig. 2-1(a) as having 2 unshielded wires and 2 shielded cables having pigtail sections of various lengths. The line is divided into sections of uniform cross section. The chain parameter matrices $\underset{\sim}{\phi}_i$ (which in this case are 12 x 12) are obtained for each section and the overall chain parameter matrix of the line, $\underset{\sim}{\phi}$, is determined as the product (in the appropriate order) of the chain parameter matrices of the individual sections as described in [1]. Once the overall chain parameter matrix for the entire line is determined, the two terminal constraints are incorporated and the terminal voltages (and/or currents) of the line are determined. This is the essential technique involved in the program.

2.1 Shielded Section

First consider the case of u unshielded wires and s shielded cables (with no pigtail sections) as shown in Fig. 2-2. The line axis is the x-coordinate axis and the phasor conductor currents for sinusoidal steady-state excitation of the line are defined in the +x direction. The current in the reference conductor is the negative sum of these U + 2S conductor currents. U conductor currents, I_{wi}, are defined for the unshielded wires and 2S currents, $I_{\hat{w}i}$ and I_{si}, are defined for the shielded cables as shown in Fig. 2-2. The phasor voltages of the U + 2S conductors, V_{wi}, $V_{\hat{w}i}$ and V_{si}, are defined with respect to the reference conductor.

To facilitate deriving the line equations, it is convenient to redefine the voltages and currents of the shielded cables as shown in Fig. 2-3. The shielded wire voltage is defined as

$$V'_{\hat{w}i} = V_{\hat{w}i} - V_{si} \tag{2-1}$$

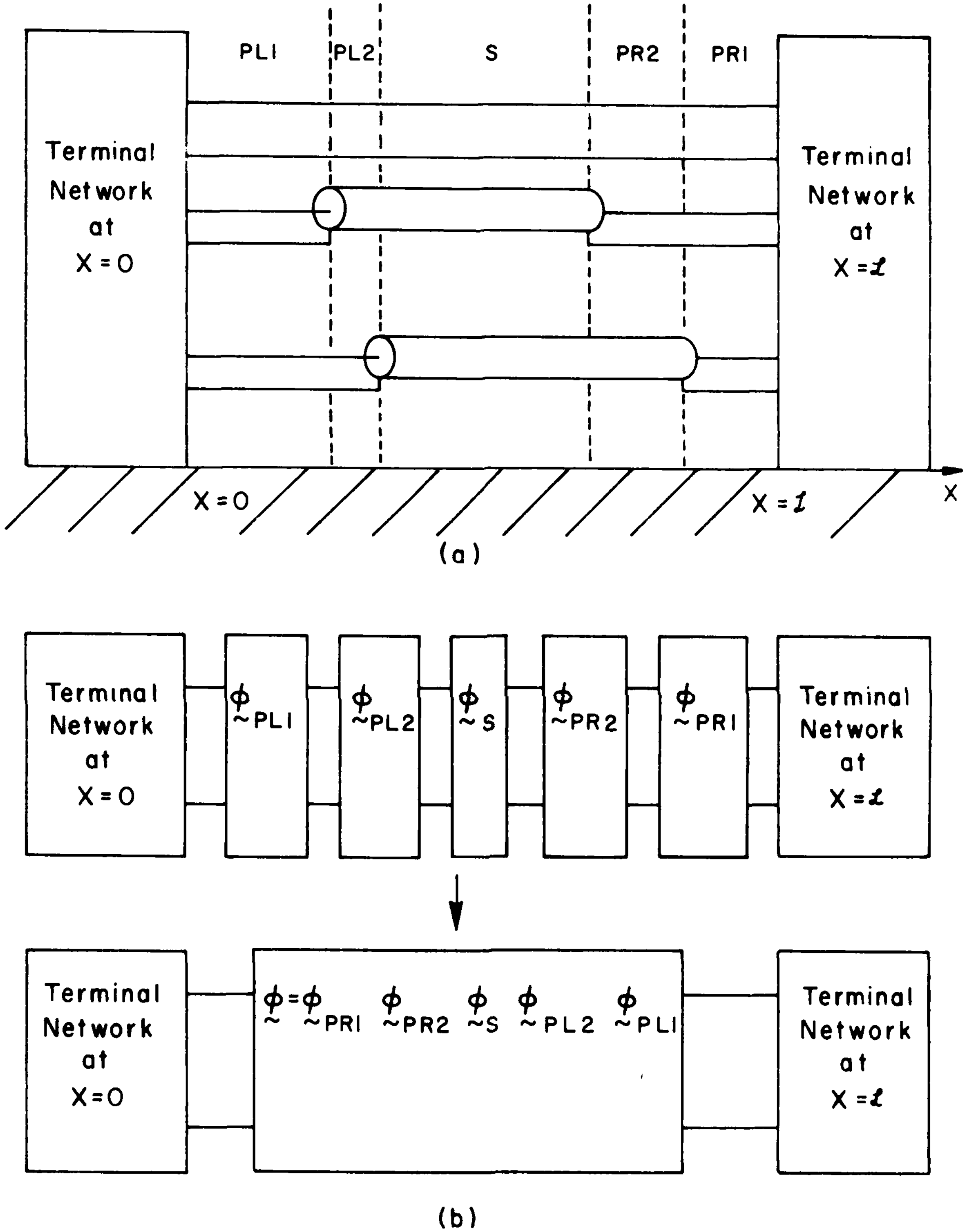


Figure 2-1. Illustration of the basic computational technique for incorporation of pigtail sections.

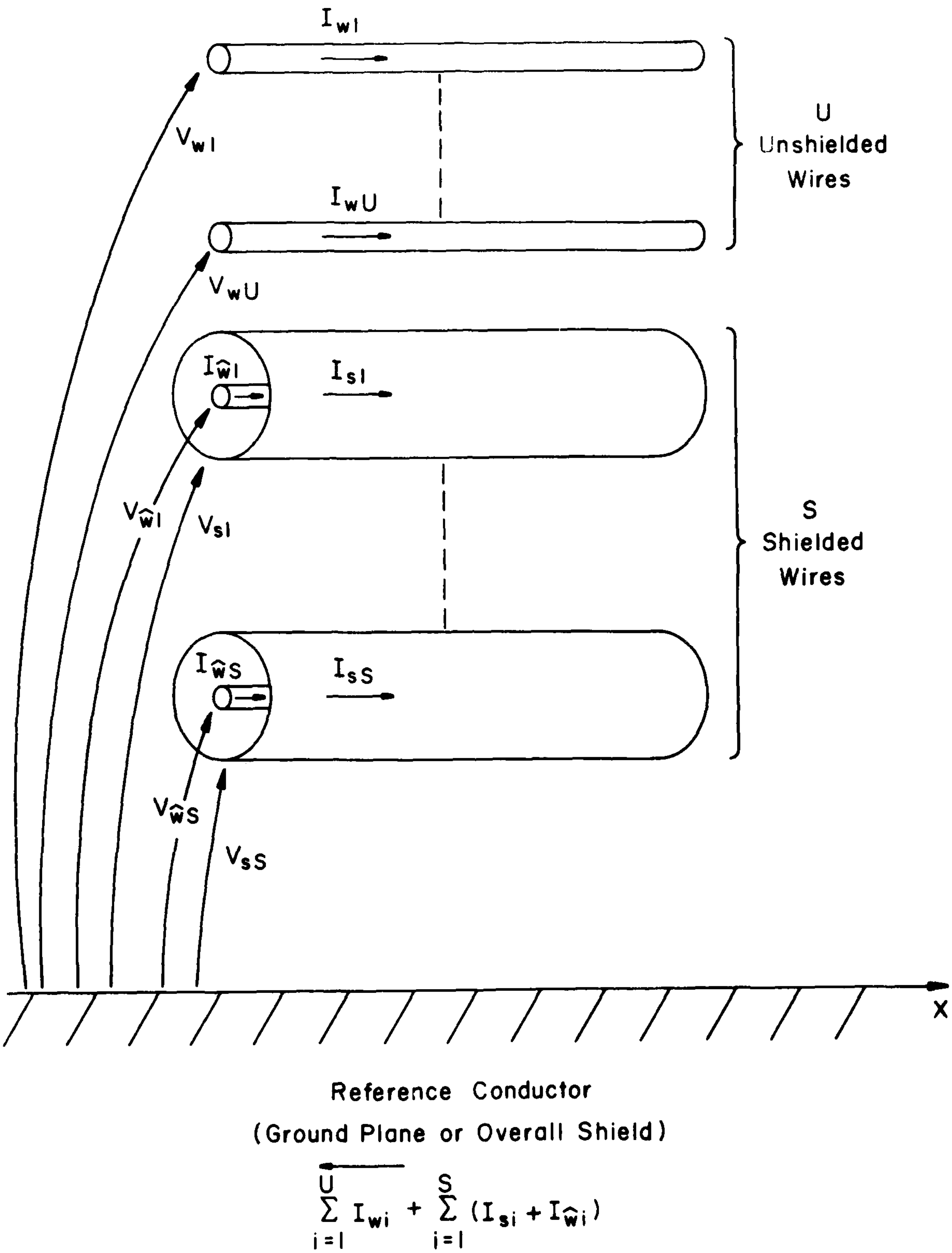


Figure 2-2. Definition of conductor currents and voltages.

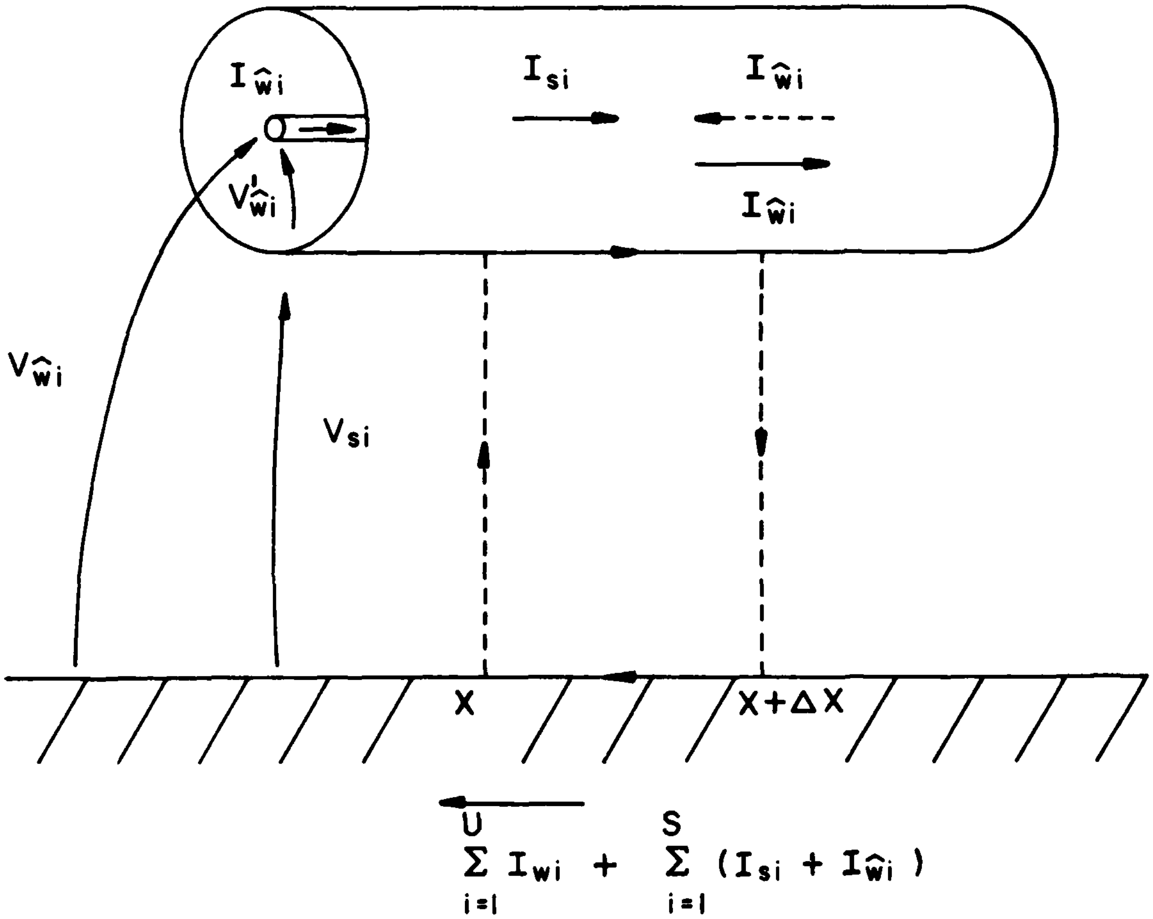


Figure 2-3. Derivation of the voltage change equation for a shielded cable.

and the voltage of the shield remains unchanged. The shielded wire currents are redefined such that a current in the shield has I_{si} and $I_{\hat{\omega}i}$ with a return exterior to the shield and $I_{\hat{\omega}i}$ with a return interior to the shield.

Defining a contour as shown in Fig. 2-3 between the shield and the reference conductor and between x and x+Δx and writing Faraday's law around this contour we obtain, in the limit as $\Delta x \to 0$ [1],

$$\frac{dV_{si}}{dx} = - j\omega\, \psi_{si} - z_{si}\,(I_{si} + I_{\hat{\omega}i}) + z_{di}\,(I_{\hat{\omega}i}) + j\omega\ell_{Ti}\, I_{\hat{\omega}i} - z_0\,\{\sum_{i=1}^{U} I_{\omega i} + \sum_{i=1}^{S} (I_{si} + I_{\hat{\omega}i})\} \qquad (2\text{-}2)$$

where ψ_{si} is the per-unit-length magnetic flux penetrating the surface bounded by the contour due to <u>all</u> currents in the system. This is determined by assuming the conductors are perfect conductors and the shields are solid with no penetrations. The other per-unit-length quantities on the right-hand-side of (2-2) are the self impedance of the shield, z_{si}, the diffusion impedance of the shield z_{di}, the self impedance of the reference conductor z_0 and the transfer inductance of the braided shield (due to holes in the braid) ℓ_{Ti}. If the shield is solid, ℓ_{Ti} is removed and z_{si} and z_{di} are changed.

The voltage change expression for the shielded wire voltage (with respect to the shield), $\acute{V}_{\hat{\omega}i}$, is obtained in a similar fashion:

$$\frac{d\acute{V}_{\hat{\omega}i}}{dx} = -j\omega\, \acute{\psi}_{\omega i} - z_{\hat{\omega}i}\, I_{\hat{\omega}i} - z_{si}\, I_{\hat{\omega}i} + z_{di}\, I_{\hat{\omega}i} + z_{di}\, I_{si} + j\omega\ell_{Ti}\, I_{\hat{\omega}i} + j\omega\ell_{Ti}\, I_{si} \qquad (2\text{-}3)$$

Here $\acute{\psi}_{\hat{\omega}i}$ is the per-unit-length magnetic flux penetrating a similar contour between the shield and the shielded wire and between x and x+Δx, and $z_{\hat{\omega}i}$ is the per-unit-length self impedance of the shielded wire. The other quantities are the same as for (2-2). Again, if the shield is solid rather than braided, ℓ_{Ti} is removed from this expression and z_{si} and z_{di} are changed.

With the relation in (2-1), the voltage change expression for $V_{\hat{\omega}i}$ becomes

$$\frac{dV_{\hat{\omega}i}}{dx} = \frac{dV'_{\hat{\omega}i}}{dx} + \frac{dV_{si}}{dx} \tag{2-4}$$

$$= - j\omega \, (\psi_{si} + \psi'_{\hat{\omega}i})$$

$$- (z_{si} - z_{di} - j\omega\ell_{Ti}) \, I_{si}$$

$$- 2(z_{si} - z_{di} - j\omega\ell_{Ti}) \, I_{\hat{\omega}i}$$

$$- z_{\hat{\omega}i} \, I_{\hat{\omega}i}$$

$$- z_0 \{ \sum_{i=1}^{U} I_{\omega i} + \sum_{i=1}^{S} (I_{si} + I_{\hat{\omega}i}) \}$$

The voltage change expressions for the voltages with respect to the reference conductor of the unshielded wires are obtained in a similar fashion:

$$\frac{dV_{wi}}{dx} = - j\omega \, \psi_{\omega i} - z_{\omega i} \, I_{\omega i} \tag{2-5}$$

$$- z_0 \{ \sum_{i=1}^{U} I_{\omega i} + \sum_{i=1}^{S} (I_{si} + I_{\hat{\omega}i}) \}$$

The above equations can be placed in matrix form in the following manner. Define the U + 2S vector of line voltages (all with respect to the reference conductor) as

$$\underline{V} = \begin{bmatrix} \underline{V}_w \\ \underline{V}_s \\ \underline{V}_{\hat{w}} \end{bmatrix} \qquad (2\text{-}6)$$

where

$$\underline{V}_w = \left.\begin{bmatrix} V_{w1} \\ \vdots \\ V_{wU} \end{bmatrix}\right\} U \qquad (2\text{-}7a)$$

$$\underline{V}_s = \left.\begin{bmatrix} V_{s1} \\ \vdots \\ V_{sS} \end{bmatrix}\right\} S \qquad (2\text{-}7b)$$

$$\underline{V}_{\hat{w}} = \left.\begin{bmatrix} V_{\hat{w}1} \\ \vdots \\ V_{\hat{w}S} \end{bmatrix}\right\} S \qquad (2\text{-}7c)$$

Write the vector of $U + 2S$ line currents as

$$\underline{I} = \begin{bmatrix} \underline{I}_w \\ \underline{I}_s \\ \underline{I}_{\hat{w}} \end{bmatrix} \qquad (2\text{-}8)$$

where

$$\underline{I}_w = \left.\begin{bmatrix} I_{w1} \\ \vdots \\ I_{wU} \end{bmatrix}\right\} U \qquad (2\text{-}9a)$$

$$\underline{I}_s = \left.\begin{bmatrix} I_{s1} \\ \vdots \\ I_{sS} \end{bmatrix}\right\} S \tag{2-9b}$$

$$\underline{I}_{\hat{w}} \quad \left.\begin{bmatrix} I_{\hat{w}1} \\ \vdots \\ I_{\hat{w}S} \end{bmatrix}\right\} S \tag{2-9c}$$

Then equations (2-2), (2-4) and (2-5) become

$$\dot{\underline{V}} = - j\omega \underline{\psi} - \underset{\sim}{Z}_c \underline{I} - z_0 \underset{\sim}{U} \underline{I} \tag{2-10}$$

where the dot denotes ordinary derivative with respect to x and the (U + 2S) x (U + 2S) matrix $\underset{\sim}{Z}_c$ is

$$\underset{\sim}{Z}_c = \begin{bmatrix} \underset{\sim}{Z}_w & \underset{\sim}{0} & \underset{\sim}{0} \\ \underset{\sim}{0} & \underset{\sim}{Z}_s & (\underset{\sim}{Z}_s - \underset{\sim}{Z}_d - j\omega \underset{\sim}{L}_T) \\ \underset{\sim}{0} & (\underset{\sim}{Z}_s - \underset{\sim}{Z}_d - j\omega \underset{\sim}{L}_T) & [2(\underset{\sim}{Z}_s - \underset{\sim}{Z}_d - j\omega \underset{\sim}{L}_T) + \underset{\sim}{Z}_{\hat{w}}] \end{bmatrix} \tag{2-11}$$

The submatrices in (2-11) are diagonal with the main diagonal entries given by

$$[\ \underset{\sim}{Z}_w\ ]_{ii} = z_{wi} \qquad i = 1, ---, U \tag{2-12a}$$

$$[\ \underset{\sim}{Z}_s\ ]_{ii} = z_{si} \qquad i = 1, ---, S \tag{2-12b}$$

$$[\ \underset{\sim}{Z}_d\ ]_{ii} = z_{di} \qquad i = 1, ---, S \tag{2-12c}$$

$$[\ \underset{\sim}{Z}_{\hat{w}}\ ]_{ii} = z_{\hat{w}i} \qquad i = 1, ---, S \tag{2-12d}$$

$$[\ \underset{\sim}{L}_T\ ]_{ii} = \ell_{Ti} \qquad i = 1, ---, S \tag{2-12e}$$

and all other entries are zero.

We denote the entry in the i-th row and j-th column of a matrix $\underset{\sim}{M}$ by $[\ \underset{\sim}{M}\ ]_{ij}$. The matrix $\underset{\sim}{U}$ is the (U + 2S) x (U + 2S) unity matrix with ones in every position:

$$\underset{\sim}{U} = \begin{bmatrix} 1 & 1 & 1 & \cdots & 1 \\ 1 & 1 & 1 & \cdots & 1 \\ \vdots & \vdots & \vdots & & \vdots \\ 1 & 1 & 1 & \cdots & 1 \end{bmatrix} \tag{2-13}$$

Once again, if the i-th shield is solid, ℓ_{Ti} is removed from $\underset{\sim}{L}_T$ and z_{di} and z_{si} are computed for a solid shield.

The (U + 2S) vector $\underline{\psi}$ relates the per-unit-length magnetic fluxes passing between each conductor and the reference conductor to the line currents via the (U + 2S) x (U + 2S) per-unit-length inductance matrix $\underline{L}$:

$$\underline{\psi} = \underset{\sim}{L}\ \underline{I} \tag{2-14}$$

where

$$[\ \underset{\sim}{L}\ ] = \ell_{ij} \tag{2-15}$$

for $\quad i,j = 1, ---, U+2S.$

Computation of the entries in $\underset{\sim}{L}$ are described in [1] and [24]. The self inductance of a shield is computed as though the shield were a solid wire. The mutual inductances between a shield and an unshielded wire are similarly computed. The only variation from this obvious scheme is the computation of the mutual inductance between a shield and its shielded wire. This is equivalent to the self inductance of the shield as described in [1]. The computation of the per-unit-length transfer inductances is described in [22,23].

The primary definition of the per-unit-length inductance matrix is

$$\underbrace{\begin{bmatrix} \underline{\psi}_w \\ \underline{\psi}_s \\ \underline{\psi}_{\hat{w}} \end{bmatrix}}_{\underline{\psi}} = \underbrace{\begin{bmatrix} \tilde{L}_{ww} & \tilde{L}_{ws} & \tilde{L}_{w\hat{w}} \\ \tilde{L}_{sw} & \tilde{L}_{ss} & \tilde{L}_{s\hat{w}} \\ \tilde{L}_{\hat{w}w} & \tilde{L}_{\hat{w}s} & \tilde{L}_{\hat{w}\hat{w}} \end{bmatrix}}_{\tilde{L}} \underbrace{\begin{bmatrix} \tilde{I}_w \\ \tilde{I}_s \\ \tilde{I}_{\hat{w}} \end{bmatrix}}_{\underline{I}} \qquad (2\text{-}16)$$

where $\underline{\psi}_w$ is a vector of per-unit-length magnetic flux passing between each wire and the reference conductor, $\underline{\psi}_s$ is a vector of per-unit-length magnetic flux passing between each shield and the reference conductor, and $\underline{\psi}_{\hat{w}}$ is a vector of magnetic flux passing between each shielded wire and the reference conductor. From the definition in (2-16) one can easily obtain the entries in $\tilde{L}$ [1]. With these definitions, the voltage change expression in (2-10) becomes

$$\dot{\underline{V}}(x) = -\,(\tilde{Z}_c + z_o\,\tilde{U} + j\omega\,\tilde{L})\,\underline{I}(x) \qquad (2\text{-}17)$$

It now remains to determine the second transmission-line equation - the current change expression.

The current change expressions are similarly computed. Essentially we need to relate the voltage of each conductor to the per-unit-length charge carried by that conductor. The per-unit-length charges and conductor voltages are defined in Fig. 2-4. These definitions are directly analogous to those for the line voltages and currents in Fig. 2-3. The shield carries per-unit-length charges q_{si} and $q_{\hat{w}i}$ on its outer surface and $-q_{\hat{w}i}$ on its inner surface. Voltages $V_{\hat{w}i}$, $V_{\hat{w}i}$ and V_{si} are defined as in Fig. 2-3.

The basic relationship is:

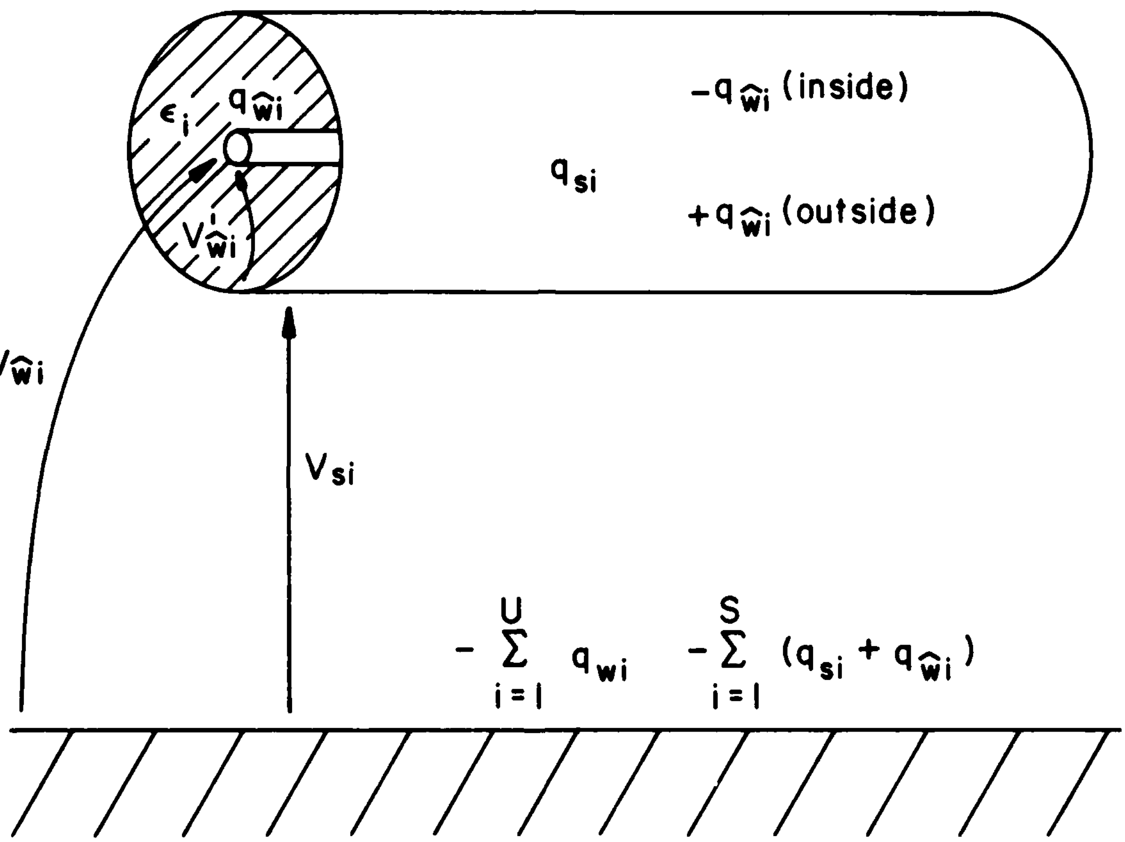


Figure 2-4. Derivation of the current change equation for a shielded cable.

$$\underline{V}_w = \underset{\sim}{S}_{ww}\,\underline{q}_w + \underset{\sim}{S}_{ws}\,\underline{q}_s + \underset{\sim}{S}_{w\hat{w}}\,\underline{q}_{\hat{w}}$$

$$\underline{V}_s = \underset{\sim}{S}_{sw}\,\underline{q}_w + \underset{\sim}{S}_{ss}\,\underline{q}_s + \underset{\sim}{S}_{s\hat{w}}\,\underline{q}_{\hat{w}} \qquad (2\text{-}18)$$

$$\underline{V}_{\hat{w}} = \underset{\sim}{S}_{\hat{w}w}\,\underline{q}_w + \underset{\sim}{S}_{\hat{w}s}\,\underline{q}_s + \underset{\sim}{S}_{\hat{w}\hat{w}}\,\underline{q}_{\hat{w}}$$

where the vectors $\underline{V}_w$, $\underline{V}_s$, $\underline{V}_{\hat{w}}$ are defined in (2-7) and

$$\underline{q}_w = \left.\begin{bmatrix} q_{w1} \\ \vdots \\ q_{wU} \end{bmatrix}\right\} U \qquad (2\text{-}19a)$$

$$\underline{q}_s = \left.\begin{bmatrix} q_{s1} \\ \vdots \\ q_{sS} \end{bmatrix}\right\} S \qquad (2\text{-}19b)$$

$$\underline{q}_{\hat{w}} = \left.\begin{bmatrix} q_{\hat{w}1} \\ \vdots \\ q_{\hat{w}S} \end{bmatrix}\right\} S \qquad (2\text{-}19c)$$

In matrix notation, (2-18) becomes

$$\underbrace{\begin{bmatrix} \underline{V}_w \\ \underline{V}_s \\ \underline{V}_{\hat{w}} \end{bmatrix}}_{\underline{V}} = \underbrace{\begin{bmatrix} \underset{\sim}{S}_{ww} & \underset{\sim}{S}_{ws} & \underset{\sim}{S}_{w\hat{w}} \\ \underset{\sim}{S}_{sw} & \underset{\sim}{S}_{ss} & \underset{\sim}{S}_{s\hat{w}} \\ \underset{\sim}{S}_{\hat{w}w} & \underset{\sim}{S}_{\hat{w}s} & \underset{\sim}{S}_{\hat{w}\hat{w}} \end{bmatrix}}_{\underset{\sim}{S}} \underbrace{\begin{bmatrix} \underline{q}_w \\ \underline{q}_s \\ \underline{q}_{\hat{w}} \end{bmatrix}}_{\underline{q}} \qquad (2\text{-}20)$$

The current change expression is obtained by inverting (2-20) as

$$\underline{q} = \underset{\sim}{S}^{-1}\,\underline{V} \tag{2-21}$$

$$= \underset{\sim}{C}\,\underline{V}$$

where we denote the per-unit-length capacitance matrix as

$$\underset{\sim}{C} = \underset{\sim}{S}^{-1} \tag{2-22}$$

Multiplying both sides of (2-21) by $j\omega$ we obtain

$$j\omega\underline{q}(x) = j\omega\underset{\sim}{C}\,\underline{V}(x) \tag{2-23}$$

Defining

$$\dot{\underline{I}}(x) = -\,j\omega\underline{q}(x) \tag{2-24}$$

we obtain the current change expression

$$\dot{\underline{I}}(x) = -j\omega\underset{\sim}{C}\,\underline{V}(x) \tag{2-25}$$

The holes in the braid of a braided shield cable introduce additional terms in $\underset{\sim}{S}$. We may treat the unshielded wires and shields of the cable as a set of U + S wires in a homogeneous medium (free space here) so that [1]

$$\begin{bmatrix} \underset{\sim}{S}_{ww} & \underset{\sim}{S}_{ws} \\ \underset{\sim}{S}_{sw} & \underset{\sim}{S}_{ss} \end{bmatrix} = \frac{1}{\mu_v \epsilon_v} \begin{bmatrix} \underset{\sim}{L}_{ww} & \underset{\sim}{L}_{ws} \\ \underset{\sim}{L}_{sw} & \underset{\sim}{L}_{ss} \end{bmatrix} \tag{2-26}$$

which is symmetric, i.e., $\underset{\sim}{L}_{ww} = \underset{\sim}{L}^t_{ww}$, $\underset{\sim}{L}_{ss} = \underset{\sim}{L}^t_{ss}$, $\underset{\sim}{L}_{ws} = \underset{\sim}{L}^t_{ws}$ and $\underset{\sim}{L}_{sw} = \underset{\sim}{L}^t_{ws}$ where we denote the transpose of a matrix $\underset{\sim}{M}$ by $\underset{\sim}{M}^t$. That is, the upper left block of $\underset{\sim}{L}$ in (2-16) are computed as though the shields comprise a set of isolated wires and $\underline{q}_{\hat{w}} = \underline{0}$ in (2-20)

In order to determine the remaining entries in $\underset{\sim}{S}$, consider the definition of $\underset{\sim}{S}$ in (2-20) and the voltage and charge definitions in Fig. 2-4. In (2-20) setting $\underline{q}_w = \underline{q}_s = 0$ we obtain from the first equation

$$\underline{V}_w = \underset{\sim}{S}_{w\hat{w}} \underline{q}_{\hat{w}} \Big|_{\underline{q}_w = \underline{q}_s = \underline{0}} \tag{2-27}$$

From Fig. 2-4, we clearly have

$$\underset{\sim}{S}_{w\hat{w}} = \underset{\sim}{S}_{ws} \tag{2-28}$$

Similarly

$$\underline{V}_s = \underset{\sim}{S}_{s\hat{w}} \underline{q}_{\hat{w}} \Big|_{\underline{q}_w = \underline{q}_s = \underline{0}} \tag{2-29}$$

so that from Fig. 2-4 we have

$$\underset{\sim}{S}_{s\hat{w}} = \underset{\sim}{S}_{ss} + \underset{\sim}{S}_T \tag{2-30}$$

The matrix $\underset{\sim}{S}_T$ is diagonal and has the per-unit-length transfer elastances s_{Ti} as determined by Latham [15,16] on its main diagonal:

$$[\underset{\sim}{S}_T]_{ii} = s_{Ti} \tag{2-31a}$$

$$[\underset{\sim}{S}_T]_{\substack{ij \\ i \neq j}} = 0 \tag{2-31b}$$

For the last block row of $\underset{\sim}{S}$ we determine the entries $\underset{\sim}{S}_{\hat{w}w}$, $\underset{\sim}{S}_{\hat{w}s}$, $\underset{\sim}{S}_{\hat{w}\hat{w}}$ with the definitions in Fig. 2-4. For example, in terms of $\underline{V}'_{\hat{w}}$,

$$\underline{V}'_{\hat{w}} = \underset{\sim}{S}'_{\hat{w}w} \underline{q}_w + \underset{\sim}{S}'_{\hat{w}s} \underline{q}_s + \underset{\sim}{S}'_{\hat{w}\hat{w}} \underline{q}_{\hat{w}} \tag{2-32}$$

and

$$\underline{V}_{\hat{w}} = \underline{V}'_{\hat{w}} + \underline{V}_s \tag{2-33}$$

So it remains to determine $\underset{\sim}{S}_{\hat{w}w}$, $\underset{\sim}{S}_{\hat{w}s}$, $\underset{\sim}{S}_{\hat{w}\hat{w}}$. Setting $\underline{q}_s = \underline{q}_{\hat{w}} = \underline{0}$ in (2-32) we have

$$\underline{V}_{\hat{w}} = \underset{\sim}{S}_{\hat{w}w}\,\underline{q}_w \Bigg|_{\underline{q}_s = \underline{q}_{\hat{w}} = \underline{0}} \tag{2-34}$$

Thus

$$\underset{\sim}{S}_{\hat{w}w} = \underset{\sim}{0} \tag{2-35}$$

(Actually $S_{\hat{w}w}$ is not zero due to penetrations for braided shields. But when added to $\underset{\sim}{S}_{sw}$ according to (2-33), it is felt that this will be negligible compared to the entries in $\underset{\sim}{S}_{sw}$ and is accordingly neglected.) Now

$$\underline{V}_{\hat{w}} = \underset{\sim}{S}_{\hat{w}s}\,\underline{q}_s \Bigg|_{\underline{q}_w = \underline{q}_{\hat{w}} = \underline{0}} \tag{2-36}$$

Here penetrations through braid holes probably should be included so that [15,16]

$$\underset{\sim}{S}_{\hat{w}s} = \underset{\sim}{S}_T \tag{2-37}$$

Similarly,

$$\underline{V}_{\hat{w}} = \underset{\sim}{S}_{\hat{w}\hat{w}}\,\underline{q}_{\hat{w}} \Bigg|_{\underline{q}_w = \underline{q}_s = \underline{0}}$$

But this is simply the interior, self-elastances of each shielded cable [1]:

$$[\underset{\sim}{S}_{\hat{w}\hat{w}}]_{ii} = \frac{\ln(r_{si}/r_{\hat{w}i})}{2\pi\varepsilon_i} \tag{2-39a}$$

$$[\underset{\sim}{S}_{\hat{w}\hat{w}}]_{ij} = 0, \quad i \neq j \tag{2-39b}$$

where r_{si} is the interior shield radius, $r_{\hat{w}i}$ is the radius of the shielded wire and ε_i is the interior dielectric permittivity. Define

$$\underset{\sim}{S}_{INT} = \underset{\sim}{S}'_{\hat{w}\hat{w}} \tag{2-40}$$

With the above results and (2-33) we obtain

$$\begin{aligned} \underset{\sim}{S}_{\hat{w}w} &= \underset{\sim}{S}_{sw} + \underset{\sim}{S}'_{\hat{w}w} \\ &= \underset{\sim}{S}_{sw} \end{aligned} \tag{2-41a}$$

$$\begin{aligned} \underset{\sim}{S}_{\hat{w}s} &= \underset{\sim}{S}_{ss} + \underset{\sim}{S}'_{\hat{w}s} \\ &= \underset{\sim}{S}_{ss} + \underset{\sim}{S}_{T} \end{aligned} \tag{2-41b}$$

$$\begin{aligned} \underset{\sim}{S}_{\hat{w}\hat{w}} &= \underset{\sim}{S}_{s\hat{w}} + \underset{\sim}{S}'_{\hat{w}\hat{w}} \\ &= \underset{\sim}{S}_{s\hat{w}} + \underset{\sim}{S}_{INT} \\ &= \underset{\sim}{S}_{ss} + \underset{\sim}{S}_{T} + \underset{\sim}{S}_{INT} \end{aligned} \tag{2-41c}$$

Thus

$$\underset{\approx}{S} = \begin{bmatrix} \underset{\sim}{S}_{ww} & \underset{\sim}{S}_{ws} & \underset{\sim}{S}_{ws} \\ \underset{\sim}{S}_{ws}^{t} & \underset{\sim}{S}_{ss} & (\underset{\sim}{S}_{ss} + \underset{\sim}{S}_{T}) \\ \underset{\sim}{S}_{ws}^{t} & (\underset{\sim}{S}_{ss} + \underset{\sim}{S}_{T}) & (\underset{\sim}{S}_{ss} + \underset{\sim}{S}_{T} + \underset{\sim}{S}_{INT}) \end{bmatrix} \tag{2-42}$$

In order to show that this result is reasonable, suppose all shields are solid so that $\underset{\sim}{S}_T = \underset{\sim}{0}$.

Then

$$\underset{\sim}{S} = \left[\begin{array}{cc|c} \underset{\sim}{S}_{ww} & \underset{\sim}{S}_{ws} & \underset{\sim}{S}_{ws} \\ \underset{\sim}{S}_{ws}^{t} & \underset{\sim}{S}_{ss} & \underset{\sim}{S}_{ss} \\ \hline \underset{\sim}{S}_{ws}^{t} & \underset{\sim}{S}_{ss} & \underset{\sim}{S}_{ss} + \underset{\sim}{S}_{INT} \end{array}\right] \tag{2-43}$$

In order for the results to be reasonable for solid shields, the structure of the per-unit-length capacitance matrix $\underset{\sim}{C}$ must be [1]

$$\underset{\sim}{C} = \left[\begin{array}{c|c} \begin{bmatrix} \underset{\sim}{S}_{ww} & \underset{\sim}{S}_{ws} \\ \underset{\sim}{S}_{ws}^{t} & \underset{\sim}{S}_{ss} \end{bmatrix}^{-1} & \begin{matrix} \underset{\sim}{0} \\ \underset{\sim}{0} \end{matrix} \\ \hline \begin{matrix} \underset{\sim}{0} & \underset{\sim}{0} \end{matrix} & \underset{\sim}{0} \end{array}\right] + \begin{bmatrix} \underset{\sim}{0} & \underset{\sim}{0} & \underset{\sim}{0} \\ \underset{\sim}{0} & \underset{\sim}{C}_{INT} & -\underset{\sim}{C}_{INT} \\ \underset{\sim}{0} & -\underset{\sim}{C}_{INT} & \underset{\sim}{C}_{INT} \end{bmatrix} \tag{2-44}$$

where

$$\underset{\sim}{C}_{INT} = \underset{\sim}{S}_{INT}^{-1} \tag{2-45}$$

is diagonal. The matrix in (2-44) can be inverted in block form using the results in [25]. Matching blocks in (2-43) we obtain

$$\begin{aligned} \begin{bmatrix} \underset{\sim}{S}_{ww} & \underset{\sim}{S}_{ws} \\ \underset{\sim}{S}_{ws}^{t} & \underset{\sim}{S}_{ss} \end{bmatrix} &\overset{?}{=} \left\{ \begin{bmatrix} \underset{\sim}{S}_{ww} & \underset{\sim}{S}_{ws} \\ \underset{\sim}{S}_{ws}^{t} & \underset{\sim}{S}_{ss} \end{bmatrix}^{-1} + \begin{bmatrix} \underset{\sim}{0} & \underset{\sim}{0} \\ \underset{\sim}{0} & \underset{\sim}{C}_{INT} \end{bmatrix} \right. \\ &\qquad \left. - \begin{bmatrix} \underset{\sim}{0} \\ -\underset{\sim}{C}_{INT} \end{bmatrix} \left[\underset{\sim}{C}_{INT}\right]^{-1} \begin{bmatrix} \underset{\sim}{0} & -\underset{\sim}{C}_{INT} \end{bmatrix} \right\}^{-1} \\ &= \left\{ \begin{bmatrix} \underset{\sim}{S}_{ww} & \underset{\sim}{S}_{ws} \\ \underset{\sim}{S}_{ws}^{t} & \underset{\sim}{S}_{ss} \end{bmatrix}^{-1} + \begin{bmatrix} \underset{\sim}{0} & \underset{\sim}{0} \\ \underset{\sim}{0} & \underset{\sim}{C}_{INT} \end{bmatrix} - \begin{bmatrix} \underset{\sim}{0} \\ -\underset{\sim}{C}_{INT} \end{bmatrix} [\underset{\sim}{0} \; - \underset{\sim}{1}] \right\}^{-1} \end{aligned} \tag{2-46a}$$

which is true. The identity matrix is denoted by $\underset{\sim}{1}$. Similarly

$$\begin{bmatrix} \underset{\sim}{S}_{ws} \\ \underset{\sim}{S}_{ss} \end{bmatrix} \overset{?}{=} - \begin{bmatrix} \underset{\sim}{S}_{ww} & \underset{\sim}{S}_{ws} \\ \underset{\sim}{S}_{ws}^{t} & \underset{\sim}{S}_{ss} \end{bmatrix} \begin{bmatrix} \underset{\sim}{0} \\ -\underset{\sim}{C}_{INT} \end{bmatrix} \begin{bmatrix} \underset{\sim}{C}_{INT} \end{bmatrix}^{-1} \tag{2-46b}$$

which is true. Also

$$\begin{bmatrix} \underset{\sim}{S}_{ws}^{t} & \underset{\sim}{S}_{ss} \end{bmatrix} \overset{?}{=} - \begin{bmatrix} \underset{\sim}{C}_{INT} \end{bmatrix}^{-1} \begin{bmatrix} \underset{\sim}{0} & -\underset{\sim}{C}_{INT} \end{bmatrix} \begin{bmatrix} \underset{\sim}{S}_{ww} & \underset{\sim}{S}_{ws} \\ \underset{\sim}{S}_{ws}^{t} & \underset{\sim}{S}_{ss} \end{bmatrix} \tag{2-46c}$$

which is true. Finally

$$\underset{\sim}{S}_{ss} + \underset{\sim}{S}_{INT} \overset{?}{=} \begin{bmatrix} \underset{\sim}{C}_{INT} \end{bmatrix}^{-1} - \begin{bmatrix} \underset{\sim}{C}_{INT} \end{bmatrix}^{-1} \begin{bmatrix} \underset{\sim}{0} & -\underset{\sim}{C}_{INT} \end{bmatrix} \begin{bmatrix} \underset{\sim}{S}_{ws} \\ \underset{\sim}{S}_{ss} \end{bmatrix} \tag{2-46d}$$

which is also true. Thus we have shown that for solid shields, the result is reasonable.

The computation of the transfer elastances is described in [22,23]. The only remaining calculations are for S_{ww}, S_{ws}, S_{ss}. These are computed from the per-unit-length inductance matrix of the isolated system of U unshielded wires and S shields [1]:

$$\begin{bmatrix} \underset{\sim}{S}_{ww} & \underset{\sim}{S}_{ws} \\ \underset{\sim}{S}_{ws}^{t} & \underset{\sim}{S}_{ss} \end{bmatrix} = \frac{1}{\mu_v \varepsilon_v} \begin{bmatrix} \underset{\sim}{L}_{ww} & \underset{\sim}{L}_{ws} \\ \underset{\sim}{L}_{ws}^{t} & \underset{\sim}{L}_{ss} \end{bmatrix} \tag{2-47}$$

2.2 Pigtail Sections

If a pigtail occurs over a section of line as illustrated in Fig. 2-1, certain entries of $\underset{\sim}{L}$ and $\underset{\sim}{Z}_C$ in (2-17) and $\underset{\sim}{S}$ in (2-20) associated with the shield attached to the pigtail and its shielded wire are computed differently.

With regard to the entries in $\underset{\sim}{L}$, the pigtail wire is simply treated as another wire instead of a shield. Thus those entries associated with the shielded wire and the shield in $\underset{\sim}{L}_{ss}$, $\underset{\sim}{L}_{s\hat{w}}$, $\underset{\sim}{L}_{\hat{w}\hat{w}}$, are simply computed as though the shielded wire and the pigtail wire are ordinary wires and one does not enclose the other. The self impedances of the shield in $\underset{\sim}{Z}_s$ are now computed for the pigtail wire, and the corresponding entries in $\underset{\sim}{Z}_d$ and $\underset{\sim}{L}_T$ are zero.

A similar process applies to the entries in the per-unit-length elastance matrix $\underset{\sim}{S}$ in (2-20). Those entries in $\underset{\sim}{S}_{w\hat{w}}$, $\underset{\sim}{S}_{s\hat{w}}$, $\underset{\sim}{S}_{\hat{w}\hat{w}}$, associated with the pigtail wire and its shielded wire are computed as though these were simply two wires with neither one enclosing the other.

2.3 The Chain Parameter Matrices of the Sections

Consider a typical uniform section of the line of length $\mathcal{L}$. The transmission-line equations are

$$\dot{\underline{V}}(x) = -(\underset{\sim}{Z}_c + z_o \underset{\sim}{U} + j\omega \underset{\sim}{L})\underline{I}(x) \tag{2-48a}$$

$$\dot{\underline{I}}(x) = -j\omega \underset{\sim}{C} \underline{V}(x) \tag{2-48b}$$

we may compute the chain parameter representation of this uniform section of line [1]:

$$\begin{bmatrix} \underline{V}(x_R) \\ \underline{I}(x_R) \end{bmatrix} = \underbrace{\begin{bmatrix} \underset{\sim}{\phi}_{11} & \underset{\sim}{\phi}_{12} \\ \underset{\sim}{\phi}_{21} & \underset{\sim}{\phi}_{22} \end{bmatrix}}_{\underset{\sim}{\phi}} \begin{bmatrix} \underline{V}(x_L) \\ \underline{I}(x_L) \end{bmatrix} \tag{2-49}$$

where x_R is the coordinate of the right end of the section, x_L is the coordinate of the left end of the section and the section length is

$$\mathcal{L} = x_R - x_L \tag{2-50}$$

We first compute the eigenvalues and eigenvectors of the product $\underset{\sim}{Y}\,\underset{\sim}{Z}$ where

$$\underset{\sim}{Y} = j\omega \underset{\sim}{C} \quad (2\text{-}51a)$$

$$\underset{\sim}{Z} = \underset{\sim}{Z}_c + z_o \underset{\sim}{U} + j\omega \underset{\sim}{L} \quad (2\text{-}51b)$$

The (U + 2S) eigenvectors are arranged in a (U + 2S) x (U + 2S) matrix $\underset{\sim}{T}$ such that

$$\underset{\sim}{T}^{-1}\,\underset{\sim}{Y}\,\underset{\sim}{Z}\,\underset{\sim}{T} = \underset{\sim}{\gamma}^2 \quad (2\text{-}52)$$

where $\underset{\sim}{\gamma}^2$ is a (U + 2S) x (U + 2S) diagonal matrix containing the eigenvalues of $\underset{\sim}{Y}\,\underset{\sim}{Z}$ on its diagonal.

The entries in $\underset{\sim}{\phi}$ are then determined from [9] as

$$\underset{\sim}{\phi}_{11} = \frac{1}{2}\,\underset{\sim}{Y}^{-1}\,\underset{\sim}{T}\,[\underset{\sim}{e}^{\gamma\mathcal{L}} + \underset{\sim}{e}^{-\gamma\mathcal{L}}]\,\underset{\sim}{T}^{-1}\,\underset{\sim}{Y} \quad (2\text{-}53a)$$

$$\underset{\sim}{\phi}_{12} = -\frac{1}{2}\,\underset{\sim}{Y}^{-1}\,\underset{\sim}{T}\,\underset{\sim}{\gamma}\,[\underset{\sim}{e}^{\gamma\mathcal{L}} - \underset{\sim}{e}^{-\gamma\mathcal{L}}]\,\underset{\sim}{T}^{-1} \quad (2\text{-}53b)$$

$$\underset{\sim}{\phi}_{21} = -\frac{1}{2}\,\underset{\sim}{T}\,[\underset{\sim}{e}^{\gamma\mathcal{L}} - \underset{\sim}{e}^{-\gamma\mathcal{L}}]\,\underset{\sim}{\gamma}^{-1}\,\underset{\sim}{T}^{-1}\,\underset{\sim}{Y} \quad (2\text{-}53c)$$

$$\underset{\sim}{\phi}_{22} = \frac{1}{2}\,\underset{\sim}{T}\,[\underset{\sim}{e}^{\gamma\mathcal{L}} + \underset{\sim}{e}^{-\gamma\mathcal{L}}]\,\underset{\sim}{T}^{-1} \quad (2\text{-}53d)$$

The (U + 2S) x (U + 2S) diagonal matrix $\underset{\sim}{\gamma}$ is the square root of $\underset{\sim}{\gamma}^2$ and the (U + 2S) x (U + 2S) diagonal matrices $\underset{\sim}{e}^{\gamma\mathcal{L}}$ and $\underset{\sim}{e}^{-\gamma\mathcal{L}}$ have entries $e^{\gamma_i\mathcal{L}}$ and $e^{-\gamma_i\mathcal{L}}$ on the main diagonals, respectively.

2.4 The Overall Chain Parameter Matrix of the Line

Once the chain parameter matrices of the sections are determined, the overall chain parameter matrix of the line is the product (in the appropriate order) of the individual chain parameter matrices of the sections as is illustrated in Fig. 2-1 [1].

2.5 Incorporating the Terminal Conditions

The final step in this process is the incorporation of the terminal conditions at the two ends of the line into the overall chain parameter matrix of the line of total length $\mathcal{L}$ in order to solve for the terminal voltages and/or currents of the line. The general terminal configuration is shown in Fig. 2-5. The terminal configuration at the right end, $x = \mathcal{L}$, is similar. Each unshielded wire and each shielded wire is connected to the reference conductor and each other by an admittance. A current source is also attached to each of these wires (and directed from the reference conductor to the wire). Each shield may be connected to the reference conductor via a short circuit or an open circuit.

In order to incorporate the terminal conditions, we first rearrange the overall chain parameter matrix of the line. At this stage, the overall chain parameter matrix of the line (which is the product of the individual chain parameter matrices of the sections) is of the form

$$\begin{bmatrix} \underset{\sim}{V}_w(\mathcal{L}) \\ \underset{\sim}{V}_s(\mathcal{L}) \\ \underset{\sim}{V}_{\hat{w}}(\mathcal{L}) \\ \underset{\sim}{I}_w(\mathcal{L}) \\ \underset{\sim}{I}_s(\mathcal{L}) \\ \underset{\sim}{I}_{\hat{w}}(\mathcal{L}) \end{bmatrix} = \begin{bmatrix} & & \\ & \underset{\sim}{\phi} & \\ & & \end{bmatrix} \begin{bmatrix} \underset{\sim}{V}_w(0) \\ \underset{\sim}{V}_s(0) \\ \underset{\sim}{V}_{\hat{w}}(0) \\ \underset{\sim}{I}_w(0) \\ \underset{\sim}{I}_s(0) \\ \underset{\sim}{I}_{\hat{w}}(0) \end{bmatrix} \quad (2\text{-}54)$$

Rearrange the rows and columns of this matrix such that

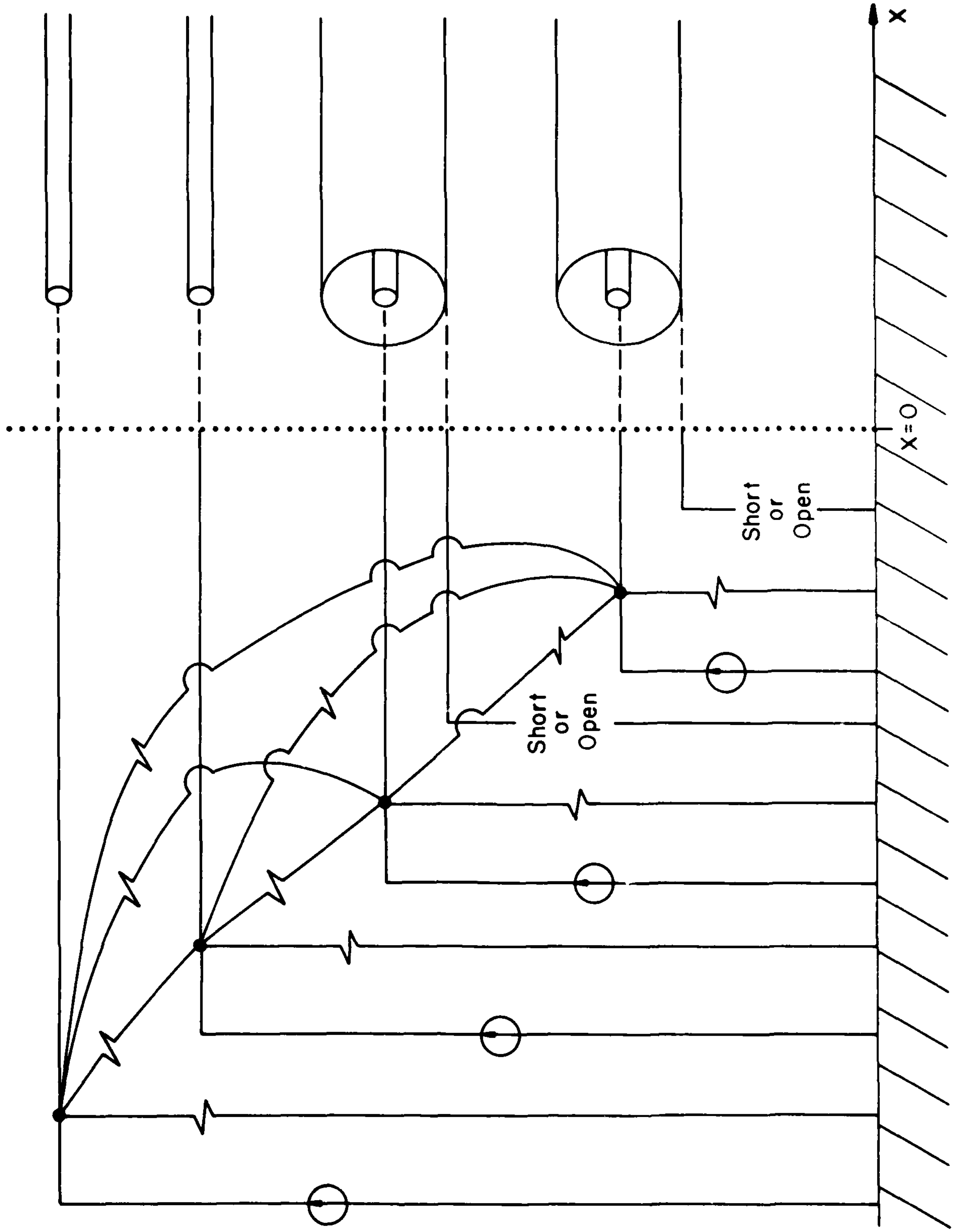


Figure 2-5. The terminal constraints of the line at x = 0.

$$\begin{matrix} U+S \left\{ \begin{matrix} \\ \\ \end{matrix} \right. \\ U+S \left\{ \begin{matrix} \\ \\ \end{matrix} \right. \\ S \left\{ \begin{matrix} \\ \\ \end{matrix} \right. \\ S \left\{ \begin{matrix} \\ \\ \end{matrix} \right. \end{matrix} \begin{bmatrix} \underline{V}_w(\mathcal{L}) \\ \underline{V}_{\hat{w}}(\mathcal{L}) \\ \hline \underline{I}_w(\mathcal{L}) \\ \underline{I}_{\hat{w}}(\mathcal{L}) \\ \hline \underline{\tilde{V}}_s(\mathcal{L}) \\ \underline{\tilde{I}}_s(\mathcal{L}) \\ \hline \underline{0} \\ \underline{0} \end{bmatrix} = \left[\begin{array}{c|c|c|c} \underset{\sim}{\psi}_{11} & \underset{\sim}{\psi}_{12} & \underset{\sim}{\psi}_{13} & \underset{\sim}{\psi}_{14} \\ \hline \underset{\sim}{\psi}_{21} & \underset{\sim}{\psi}_{22} & \underset{\sim}{\psi}_{23} & \underset{\sim}{\psi}_{24} \\ \hline \underset{\sim}{\psi}_{31} & \underset{\sim}{\psi}_{32} & \underset{\sim}{\psi}_{33} & \underset{\sim}{\psi}_{34} \\ \hline \underset{\sim}{\psi}_{41} & \underset{\sim}{\psi}_{42} & \underset{\sim}{\psi}_{43} & \underset{\sim}{\psi}_{44} \end{array} \right] \begin{bmatrix} \underline{V}_w(0) \\ \underline{V}_{\hat{w}}(0) \\ \hline \underline{I}_w(0) \\ \underline{I}_{\hat{w}}(0) \\ \hline \underline{\tilde{V}}_s(0) \\ \underline{\tilde{I}}_s(0) \\ \hline \underline{0} \\ \underline{0} \end{bmatrix} \begin{matrix} \left. \begin{matrix} \\ \\ \end{matrix} \right\} U+S \\ \left. \begin{matrix} \\ \\ \end{matrix} \right\} U+S \\ \left. \begin{matrix} \\ \\ \end{matrix} \right\} S \\ \left. \begin{matrix} \\ \\ \end{matrix} \right\} S \end{matrix} \qquad (2\text{-}55)$$

In each vector, the first U + S entries contain the unshielded wire and shielded wire voltages. The next U + S entries contain the unshielded wire and shielded wire currents. The next S entries contain the shield voltages, $\underline{\tilde{V}}_s$, for those shield terminations which are open and the shield currents, $\underline{\tilde{I}}_s$, for the remaining shield terminations which are shorts. The next S zero vectors are constraints imposed by the zero shield voltages for those shields which are short-circuited and the remaining shield currents for those shields which are open-circuited.

Thus

$$\underline{V}_s(\mathcal{L}) = \begin{bmatrix} \underline{\tilde{V}}_s(\mathcal{L}) \\ \underline{0} \end{bmatrix} \qquad \underline{V}_s(0) = \begin{bmatrix} \underline{\tilde{V}}_s(0) \\ \underline{0} \end{bmatrix}$$
$$\underline{I}_s(\mathcal{L}) = \begin{bmatrix} \underline{\tilde{I}}_s(\mathcal{L}) \\ \underline{0} \end{bmatrix} \qquad \underline{I}_s(0) = \begin{bmatrix} \underline{\tilde{I}}_s(0) \\ \underline{0} \end{bmatrix} \qquad (2\text{-}56)$$

For the general terminal configuration in Fig. 2-5 we may write a generalized Norton equivalent representation relating the unshielded wire and shielded wire currents and voltages:

$$\begin{bmatrix} \underline{I}_w(0) \\ \underline{I}_{\hat{w}}(0) \end{bmatrix} = - \underset{\sim}{Y}_0 \begin{bmatrix} \underline{V}_w(0) \\ \underline{V}_{\hat{w}}(0) \end{bmatrix} + \underline{I}_{S0} \tag{2-57}$$

The main-diagonal entries of $\underset{\sim}{Y}_0$ are the sum of all the admittances connected to the corresponding wire while each off-diagonal entry is the negative of the admittance connected between the appropriate wires. This is the usual nodal admittance matrix of lumped-circuit theory. The entries in $\underline{I}_{S0}$ are the values of the appropriate current sources connected to each wire. The constraint at $x = \mathcal{L}$ is similar:

$$\begin{bmatrix} \underline{I}_w(\mathcal{L}) \\ \underline{I}_{\hat{w}}(\mathcal{L}) \end{bmatrix} = \underset{\sim}{Y}_{\mathcal{L}} \begin{bmatrix} \underline{V}_w(\mathcal{L}) \\ \underline{V}_{\hat{w}}(\mathcal{L}) \end{bmatrix} - \underline{I}_{S\mathcal{L}} \tag{2-58}$$

Substituting (2-57) and (2-58) into (2-55) we obtain

$$\left[\begin{array}{c|c|c|c} (\underset{\sim}{\psi}_{12}\underset{\sim}{Y}_0-\underset{\sim}{\psi}_{11}) & \underset{\sim}{1} & -\underset{\sim}{\psi}_{13} & \underset{\sim}{0} \\ \hline (\underset{\sim}{\psi}_{22}\underset{\sim}{Y}_0-\underset{\sim}{\psi}_{21}) & \underset{\sim}{Y}_{\mathcal{L}} & -\underset{\sim}{\psi}_{23} & \underset{\sim}{0} \\ \hline (\underset{\sim}{\psi}_{42}\underset{\sim}{Y}_0-\underset{\sim}{\psi}_{41}) & \underset{\sim}{0} & -\underset{\sim}{\psi}_{43} & \underset{\sim}{0} \\ \hline (\underset{\sim}{\psi}_{32}\underset{\sim}{Y}_0-\underset{\sim}{\psi}_{31}) & \underset{\sim}{0} & -\underset{\sim}{\psi}_{33} & \underset{\sim}{1} \end{array}\right] \left[\begin{array}{c} \underline{V}_w(0) \\ \underline{V}_{\hat{w}}(0) \\ \hline \underline{V}_w(\mathcal{L}) \\ \underline{V}_{\hat{w}}(\mathcal{L}) \\ \hline \underline{\tilde{V}}_s(0) \\ \underline{I}_s(0) \\ \hline \underline{\tilde{V}}_s(\mathcal{L}) \\ \underline{I}_s(\mathcal{L}) \end{array}\right] = \left[\begin{array}{c} \underset{\sim}{\psi}_{12}\underline{I}_{S0} \\ \hline \underline{I}_{S\mathcal{L}} + \underset{\sim}{\psi}_{22}\underline{I}_{S0} \\ \hline \underset{\sim}{\psi}_{42}\underline{I}_{S0} \\ \hline \underset{\sim}{\psi}_{32}\underline{I}_{S0} \end{array}\right] \tag{2-59}$$

Equations (2-59) may be reduced by noting that the last set of equations may be separated from the first three.

Thus

$$\left[\begin{array}{c|c|c} (\psi_{12}Y_0-\psi_{11}) & 1 & -\psi_{13} \\ \hline (\psi_{21}Y_0-\psi_{21}) & Y_{\mathcal{L}} & -\psi_{23} \\ \hline (\psi_{42}Y_0-\psi_{41}) & 0 & -\psi_{43} \end{array}\right] \left[\begin{array}{c} \underline{V}_w(0) \\ \underline{V}_{\hat{w}}(0) \\ \hline \underline{V}_w(\mathcal{L}) \\ \underline{V}_{\hat{w}}(\mathcal{L}) \\ \hline \tilde{\underline{V}}_s(0) \\ \tilde{\underline{I}}_s(0) \end{array}\right] \left[\begin{array}{c} \psi_{12}\,\underline{I}_{S0} \\ \hline \underline{I}_{S\mathcal{L}} + \psi_{22}\,\underline{I}_{S0} \\ \hline \psi_{42}\,\underline{I}_{S0} \end{array}\right] \quad (2\text{-}60a)$$

$$\begin{bmatrix} \tilde{\underline{V}}_s(\mathcal{L}) \\ \tilde{\underline{I}}_s(\mathcal{L}) \end{bmatrix} = -\,(\psi_{32}Y_0-\psi_{31}) \begin{bmatrix} \underline{V}_w(0) \\ \underline{V}_{\hat{w}}(0) \end{bmatrix} + \psi_{33} \begin{bmatrix} \tilde{\underline{V}}_s(0) \\ \tilde{\underline{I}}_s(0) \end{bmatrix} + \psi_{32}\,\underline{I}_{S0} \quad (2\text{-}60b)$$

These may again be simplified. The first set of equations in Equation (2-60a) may be solved for

$$\begin{bmatrix} \underline{V}_w(\mathcal{L}) \\ \underline{V}_{\hat{w}}(\mathcal{L}) \end{bmatrix} = -\,(\psi_{12}Y_0-\psi_{11}) \begin{bmatrix} \underline{V}_w(0) \\ \underline{V}_{\hat{w}}(0) \end{bmatrix} + \psi_{13} \begin{bmatrix} \tilde{\underline{V}}_s(0) \\ \tilde{\underline{I}}_s(0) \end{bmatrix} + \psi_{12}\,\underline{I}_{S0} \quad (2\text{-}61)$$

Substituting into the last two sets of equations in (2-60a) yields the only simultaneous set of equations which need be solved:

$$\begin{array}{l} U+S \\ \\ S \end{array} \left\{ \left[\begin{array}{c|c} (\psi_{22}Y_0-\psi_{21}-Y_{\mathcal{L}}\,\psi_{12}Y_0 + Y_{\mathcal{L}}\,\psi_{11}) & (Y_{\mathcal{L}}\,\psi_{13}-\psi_{23}) \\ \hline (\psi_{42}Y_0-\psi_{41}) & -\psi_{43} \end{array}\right] \right. \left[\begin{array}{c} \underline{V}_w(0) \\ \underline{V}_{\hat{w}}(0) \\ \hline \tilde{\underline{V}}_s(0) \\ \tilde{\underline{I}}_s(0) \end{array}\right] = \left[\begin{array}{c} \underline{I}_{S\mathcal{L}} + (\psi_{22} \\ -Y_{\mathcal{L}}\,\psi_{12})\,\underline{I}_{S0} \\ \hline \psi_{42}\,\underline{I}_{S0} \end{array}\right]$$

(2-62)

Once the U + 2S equations in (2-62) are solved for the terminal voltages at x = 0, $\underline{V}_w(0)$ and $\underline{V}_{\hat{w}}(0)$, the terminal voltages at $x = \mathcal{L}$, $\underline{V}_w(\mathcal{L})$ and $\underline{V}_{\hat{w}}(\mathcal{L})$, are obtained directly from (2-61).

III. Description of The Program

The contents and operation of the code will be described in this chapter. The cards (lines) in the program deck are sequentially numbered in columns 73-80 with the word SHLD 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 A. Steps required to convert the program to single precision are given in Appendix B and a flow chart is given in Appendix C. 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, respectively. The program was implemented on an IBM 370/165 digital computer at the University of Kentucky using the WATFIV compiler, and the single precision version should be implementable on other computers. The program requires certain function subprograms and subroutines which will be described in this chapter and are supplied with the main program. In addition, the program requires two subroutines from the IMSL (International Mathematical and Statistical Library) package [26]. The first of these subroutines, LEQT1C, solves a set of simultaneous, complex equations and the other, EIGCC, determines the eigenvalues and eigenvectors of a general, complex matrix. Any other general purpose subroutines of this type may be used. See [27] for a description of LEQT1C and EIGCC and their argument lists.

3.1 Main Program Description

Cards 1-37 contain comments concerning the general applicability of the program. Cards 38-113 contain array dimensions and type declarations. The total number of unshielded wires is NU and the total number of shielded cables is NS. Certain combinations of these variables which are used in examples of dimensioning are given in cards 48-53. Either NU or NS may be chosen by the user to be zero. However, if either is chosen to be zero, certain dimensions must be set to 1 and not zero. See cards 85 and 97.

Cards 114-116 define two common blocks used to transfer certain constants. Cards 117-135 define certain constants. Most of these are obvious. Constant CMTM = 2.54D-5 when multiplied by a dimension given in mils (.001 inch) converts that dimension to meters. The quantity RADEG = ONE80/PI converts radians to degrees, and V = 2.997925D8 is the velocity of light in free space. ERTE is the permittivity of free space.

Cards 136-342 read the input data concerning dimensions and properties of the line conductors as well as lengths of pigtail sections and properties of the shields. The reader is referred to the next chapter - user's manual - for a definition of these input parameters. Cards 344-517 read the terminal admittance, current source and shield grounding data.

Cards 519-561 read the frequency (F), the reference conductor impedance (ZG) and compute the self impedances of the unshielded wires (array ZWWV), the self impedances of the pigtail wires on the left end (array ZWPLV) and right end (array ZWPRV) of the line, the self impedances of the shields (array ZSV), the diffusion impedances of the shields (array ZDV), the transfer inductances of the shields (array LTV) and the transfer elastances of the shields (array STV).

Cards 563-633 compute the overall chain parameter matrix of the pigtail sections on the right end of the line. Card 570 stores the lengths of the right pigtail sections (array LPR) into array LPT. Cards 573-576 initialize the overall chain parameter matrix of the right end to the identity matrix. Cards 578-588 determine the length of the first (rightmost) pigtail section (variable LMINR) as well as the longest pigtail section, LMAXR, and initialize the entries in array KEY to indicate whether a shielded cable is shielded over this section (KEY=1) or has a pigtail over this section (KEY=2). Array KEY is the key to keeping this information sorted out. Card 589 calls subroutine INDUCT which computes the per-unit-length inductance matrix, L. Card 593 computes $Z = j\omega L + z_o U$ as in (2-17). Card 596 adds the self impedances of the unshielded wires. (See equation (2-11). Matrix Z_w is added to the above.) Subroutine IMPADD is called in card 598 to add the remaining self and diffusion impedances, Z_s and Z_d, the self impedances of the shielded wires, $Z_{\hat{w}}$, as well as the transfer inductances L_T to complete the formation of (2-11) and thus Z. Card 599 calls subroutine SCAP which forms the per-unit-length elastance matrix of the unshielded wire, shield system; that is, equation (2-42) without S_T and S_{INT}. Subroutine ADMADD in card 600 adds S_T and S_{INT} to this result to complete the formation of S in (2-42). Cards 601-605 compute S^{-1} (and stores S^{-1} in array TI). Cards 607-610 compute $Y = j\omega C = j\omega S^{-1}$ and Y^{-1}. Subroutine MULTC forms the product YZ in card 611 and stores in array TI, and subroutine EIGCC computes the eigenvectors of YZ (stores in array T) and eigenvalues, γ^2, (stores in array GAM). Cards 613-618 compute T^{-1} and cards 619-620 compute γ and stores in array GAM. In card 621, subroutine PHI computes the chain parameter matrix of this section (stored in array PHIT) and MULTC forms the product of PHIT and the previously stored (accumulated) chain parameter matrix of the right pigtail section, PHIR, and stores in array TPHI. Cards 623-625 store TPHI in array PHIR. Array PHIR thus is a "running" accumulation of products of the chain parameter matrices of these individual sections of the right pigtails. Cards 626-627 subtract the length of the present pigtail section, LMINR, from each of the right pigtail section lengths and redefines them in array LPT. The code returns to statement 117 (card 577) and continues again through this section unless there are no nonzero pigtail section lengths for this pass. Card 581 checks for this condition and when no nonzero pigtail section lengths remain, the code goes to statement 132 (card 630) and begins processing the left pigtail sections in an identical manner. At this point the overall chain parameter matrix of the entire right pigtail section is stored in PHIR.

Cards 634-704 process the left pigtail sections in an identical fashion as for the right pigtail sections and stores the overall chain parameter matrix in array PHIL.

Cards 705-747 compute the chain parameter matrix for the shielded section (a section with no pigtails in the interior of the line) and stores it in TPHI. Card 748 computes the product TPHI * PHIL and stores in PHIT and card 749 then computes PHIR * PHIT = PHIR*TPHI*PHIL and stores in TPHI. At this stage, TPHI in card 749 contains the overall chain parameter matrix of the entire line and it remains to incorporate the terminal conditions.

If the line should contain only unshielded wires, the code bypasses the above pigtail and shield calculations and computes the chain parameter matrix directly in cards 751-786 and stores in TPHI.

Cards 788-859 rearrange the overall chain parameter matrix rows and columns as described in section 2.5. Once this is completed, the terminal conditions are incorporated into this rearranged chain parameter matrix in cards 860-909, and equation (2-62) is formed. This is solved in card 910 and equations (2-61) are formed in cards 911-924. Array EP contains

$$\begin{bmatrix} \underline{V}_{w}(0) \\ \underline{V}_{\hat{w}}(0) \end{bmatrix}$$

from equation (2-62) and array EN contains

$$\begin{bmatrix} \underline{V}_w(\mathcal{Z}) \\ \underline{V}_{\hat{w}}(\mathcal{Z}) \end{bmatrix}$$

from equation (2-61).

Cards 925-962 compute the magnitudes and angles of these terminal voltages of the unshielded and shielded wires and print the results.

3.2 Function Subprogram LS1

Cards FLS10001-FLS10014 contain a function subprogram for computing the per-unit-length self inductances of wires above a ground plane. For a wire of radius r_{wi} at a height of y_i above ground, the result is [9,24]

$$LS1 = \frac{\mu_v}{2\pi} \ln\left(\frac{2y_i}{r_{wi}}\right) \text{ H/m}$$

3.3 Function Subprogram LM1

Cards FLM10001-FLM10017 contain a function subprogram for computing the per-unit-length mutual inductances between two wires above a ground plane. For two wires at heights y_i and y_j and horizontal coordinates z_i and z_j, the result is [1,9,24]

$$LM1 = \frac{\mu_v}{2\pi} \ln\left[1 + \frac{4y_iy_j}{d_{ij}^2}\right] \text{ H/m}$$

where

$$d_{ij} = \sqrt{(y_i - y_j)^2 + (z_i - z_j)^2}$$

3.4 Function Subprogram LS2

Cards FLS20001-FLS20014 contain a function subprogram for computing the per-unit-length self inductances of wires within an overall, circular, cylindrical shield. For an overall shield of interior radius R and a wire of radius r_{wi} located r_i from the axis of the shield, the result is [9,24]

$$LS2 = \frac{\mu_v}{2\pi} \ln \left[\frac{R^2 - r_i^2}{R\, r_{wi}} \right] \quad H/m$$

3.5 Function Subprogram LM2

Cards FLM20001-FLM20019 contain a function subprogram for computing the per-unit-length mutual inductances between wires within an overall, circular, cylindrical shield. For an overall shield with interior radius R and wires which are at radii r_i and r_j from the axis of the shield and separated by angle Θ_{ij}, the result is [9,24]

$$LM2 = \frac{\mu_v}{2\pi} \ln \left\{ \left(\frac{r_j}{R}\right)^2 \left[\frac{(r_i r_j)^2 + R^4 - 2 r_i r_j R^2 \cos(\Theta_{ij})}{(r_i r_j)^2 + r_j^4 - 2 r_i r_j^3 \cos(\Theta_{ij})} \right] \right\} \quad H/m$$

3.6 Function Subprogram STB

Cards FSTB0001-FSTB0073 contain a function subprogram for computing the per-unit-length transfer elastances for braided shields which are entires in $\underset{\sim}{S}_T$ in equation (2-42). A table of values of this parameter for discrete values of braid weave angle for angles less than or equal to 45° is given in [22]. An interpolation routine described in [23] is used to interpolate this table.

3.7 Function Subprogram LTB

Cards FLTB0001-FLTB0073 is a function subprogram for computing the per-unit-length transfer inductances for braided shields which are entries in $\underset{\sim}{L}_T$ in equation (2-11). A table of values of this parameter for discrete values of braid weave angle for angles less than or equal to 45° is given in [22]. An interpolation routine described in [23] is used to interpolate this table.

3.8 Function Subprogram ZWW

Cards FZWW0001-FZWW0027 contain a function subprogram for computing the per-unit-length self impedances of stranded wires. The per-unit-length self impedance of one strand is determined, z_{ST}, and the NST strands are treated as being connected in parallel so that the total per-unit-length self impedance of the stranded wire is ZWW = z_{ST}/NST Ω/m. The programmed equations are described in [1,27]. For a solid cylinder of radius r_w and conductivity σ, the skin depth is

$$\delta = \frac{1}{\sqrt{\pi f \mu_v \sigma}}$$

$$= \frac{1}{2\pi \sqrt{\sigma f \times 10^{-7}}}$$

the D-C per-unit-length resistance is

$$r_{DC} = \frac{1}{\pi \sigma r_w^2} \qquad \Omega/\text{m}$$

and the D-C per-unit-length internal inductance is

$$\ell_{DC} = \frac{\mu_v}{8\pi}$$

$$= .5 \times 10^{-7} \qquad \text{H/m}$$

Including skin effect, the programmed equations are [1,27]

(I) $r_w \le \delta$

$r = r_{DC}$ Ω/m

$\ell = \ell_{DC}$ H/m

(II) $\delta < r_w < 3\delta$

$$r = \frac{1}{4} \left(\frac{r_w}{\delta} + 3\right) r_{DC} \quad \Omega/m$$

$$\ell = \left[1.15 - .15 \left(\frac{r_w}{\delta}\right)\right] \ell_{DC} \quad H/m$$

(III) $r_w \geq 3\delta$

$$r = \frac{r_w}{2\delta} r_{DC} \quad \Omega/m$$

$$\ell = \frac{2\delta}{r_w} \ell_{DC} \quad H/m$$

The per-unit-length self impedance of each strand of radius r_w is

$$z_{ST} = r + j\omega\ell \quad \Omega/m$$

3.9 <u>Function Subprogram ZDB</u>

Cards FZDB0001-FZDB0023 contain a function subprogram for computing the per-unit-length diffusion impedances of braided shields. For a braided shield having B belts, WPB wires per belt and weave angle Θ_w, the result is [1]

$$ZDB = r_{DC} \frac{\gamma \; 2r_b}{\sinh(2\gamma r_b)} \quad \Omega/m$$

where the braid wires have radius r_b,

$$\gamma = (1 + j1)/\delta$$

$$\delta = \frac{1}{\sqrt{\pi f \mu_v \sigma}}$$

and r_{DC} is the per-unit-length D-C resistance of the braid [1]

$$r_{DC} = \frac{1}{\pi \; \sigma r_b^2 \; B \; WPB \; \cos(\Theta_w)} \quad \Omega/m$$

(All braid wires are treated as being connected in parallel.)

3.10 Function Subprogram ZSB

Cards FZSB0001-FZSB0029 contain a function subprogram for computing the per-unit-length self impedance of a braided shield. The per-unit-length impedance of each isolated braid wire, z_b, is computed as described in section 3.7 and the result is [1]

$$ZSB = \frac{z_b}{B\ WPB\ Cos(\Theta_w)} \quad \Omega/m$$

3.11 Function Subprogram ZDS

Cards FZDS0001-FZDS0020 contain a function subprogram for computing the per-unit-length diffusion impedances of solid shields. The shield is treated as a thin-walled (relative to the shield radius) cylinder and the equations are [17]

$$ZDS = r_{DC} \frac{\gamma\ t_s}{\sinh\ (\gamma t_s)} \quad \Omega/m$$

where the shield is of conductivity σ, interior radius r_s, thickness t_s and

$$r_{DC} = \frac{1}{\pi\ \sigma\ t_s\ (2r_s + t_s)} \quad \Omega/m$$

$$\delta = \frac{1}{\sqrt{\pi f \mu_v \sigma}}$$

$$\gamma = (1+j1)/\delta$$

3.12 Function Subprogram ZSS

Cards FZSS0001-FZSS0024 contain a function subprogram for computing the per-unit-length self impedances of solid shields. The shield is, as in ZDS, treated as a thin-walled cylinder and the equations are described in [27]:

$$ZSS = r + j\omega\ell \quad \Omega/m$$

where the shield has conductivity σ, interior radius r_s and thickness t_s:

$$r = \frac{1}{2\pi r_s \sigma\delta} \left[\frac{\sinh(\frac{2t_s}{\delta}) + \sin(\frac{2t_s}{\delta})}{\cosh(\frac{2t_s}{\delta}) - \cos(\frac{2t_s}{\delta})} \right] \Omega/m$$

$$\omega\ell = \frac{1}{2\pi r_s \sigma\delta} \left[\frac{\sinh(\frac{2t_s}{\delta}) - \sin(\frac{2t_s}{\delta})}{\cosh(\frac{2t_s}{\delta}) - \cos(\frac{2t_s}{\delta})} \right] \Omega/m$$

and δ is the skin depth.

3.13 Subroutine MULTC

Cards SMUL0001-SMUL0017 contain a subroutine for multiplying two complex matrices $\underset{\sim}{B}$ and $\underset{\sim}{C}$ as

$$\underset{\sim}{A} = \underset{\sim}{B}\,\underset{\sim}{C}$$

$\underset{\sim}{A}$ is of dimension NL x NR,

$\underset{\sim}{B}$ is of dimension NL x NM, and

$\underset{\sim}{C}$ is of dimension NM x NR.

3.14 Subroutine SCAP

Cards SCAP0001-SCAP0024 contain a subroutine for computing a portion of the per-unit-length elastance matrix, S, described in section 2.1. The routine computes equation (2-42) for only the system of U unshielded wires and S shields, that is, $\underset{\sim}{S}$ without submatrices $\underset{\sim}{S}_T$ and $\underset{\sim}{S}_{IND}$. Those submatrices are added to this $\underset{\sim}{S}$ in subroutine ADMADD. The matrix to be computed is

$$\begin{bmatrix} \underset{\sim}{V}_w \\ \underset{\sim}{V}_{s,p} \\ \underset{\sim}{V}_w \end{bmatrix} = \begin{bmatrix} \underset{\sim}{S}_{ww} & S_{ws,wp} & \underset{\sim}{S}_{w\hat{w}} \\ \underset{\sim}{S}^t_{ws,wp} & \underset{\sim}{S}_{ss,pp} & \underset{\sim}{S}_{s\hat{w},p\hat{w}} \\ \underset{\sim}{S}^t_{w\hat{w}} & \underset{\sim}{S}_{s\hat{w},p\hat{w}} & \underset{\sim}{S}_{\hat{w}\hat{w}} \end{bmatrix} \begin{bmatrix} \underset{\sim}{q}_w \\ \underset{\sim}{q}_{s,p} \\ \underset{\sim}{q}_{\hat{w}} \end{bmatrix}$$

Here w denotes unshielded wires, s denotes shields, p denotes pigtail wires and $\hat{w}$ denotes shielded wires. First the per-unit-length elastance matrix is computed from the per-unit-length inductance matrix $\underset{\sim}{L}$ as

$$\underset{\sim}{S} = \frac{1}{\mu_v \varepsilon_v} \underset{\sim}{L}$$

Then a check is made using array KEY to determine if, in fact, a shield is actually present over this section rather than a pigtail wire. If so, those entries in $S_{\hat{w}\hat{w}}$ need to be changed to the corresponding ones in $\underset{\sim}{S}_{ss,pp}$ as indicated in equation (2-42). Entries in $\underset{\sim}{S}_{w\hat{w}}$ and $\underset{\sim}{S}_{s\hat{w},p\hat{w}}$ are already computed correctly in $\underset{\sim}{L}$ by subroutine INDUCT.

3.15 Subroutine INDUCT

Cards SIND0001-SIND0169 contain a subroutine for computing the per-unit-length inductance matrix $\underset{\sim}{L}$ given in equation (2-14) - (2-17):

$$\underset{\sim}{L} = \begin{bmatrix} \underset{\sim}{L}_{ww} & \underset{\sim}{L}_{ws,wp} & \underset{\sim}{L}_{w\hat{w}} \\ \underset{\sim}{L}^t_{ws,wp} & \underset{\sim}{L}_{ss,pp} & \underset{\sim}{L}_{s\hat{w},p\hat{w}} \\ \underset{\sim}{L}^t_{w\hat{w}} & \underset{\sim}{L}^t_{s\hat{w},p\hat{w}} & \underset{\sim}{L}_{\hat{w}\hat{w}} \end{bmatrix}$$

subscripts w, p, s, $\hat{w}$ have the same meaning here as in the previous section. If over this section, no shields are involved, i.e., each shield is in fact a pigtail wire, then $\underset{\sim}{L}$ is computed in a straightforward fashion as that of a system of U unshielded wires, S shielded wires and S pigtail wires. If, over this section, a shield is present (determined by array KEY), then appropriate entries in $\underset{\sim}{L}_{w\hat{w}}$ are equal to the corresponding entries in $\underset{\sim}{L}_{ws,wp}$ since the mutual inductance between an unshielded wire and a shielded wire is the same as the mutual inductance between the unshielded wire and that shield [1]. Similarly, certain entries in $\underset{\sim}{L}_{s\hat{w},p\hat{w}}$ are equal to the corresponding entries in

$\underset{\sim}{L}_{ss,pp}$ since the mutual inductance between a shield and its shielded wire is the same as the self inductance of that shield [1].

3.16 Subroutine PHI

Cards SPHI0001-SPHI0054 contain a subroutine for computing the chain parameter matrix of a section of line as described in section 2.3. To save array space several dummy arrays are used temporarily and written over.

3.17 Subroutine ADMADD

Cards SADM0001-SADM0030 contain a subroutine for adding $\underset{\sim}{S}_T$ and $\underset{\sim}{S}_{IND}$ to the $\underset{\sim}{S}$ matrix generated by subroutine SCAP to yield the per-unit-length elastance matrix $\underset{\sim}{S}$ in equation (2-42).

3.18 Subroutine IMPADD

Cards SIMP0001-SIMP0039 contain a subroutine to add the self impedances, diffusion impedances and transfer inductances ($\underset{\sim}{Z}_s$, $\underset{\sim}{Z}_d$, $\underset{\sim}{L}_T$) to the per-unit-length impedance matrix to yield $\underset{\sim}{Z}$ in equation (2-11). The self impedances of the shielded wires, $\underset{\sim}{Z}_{\hat{w}}$, are also added

IV. User's Manual

In this section we will provide a user's manual showing the format and description of the required input data. The program requires that the input data groups be organized as shown in Table 1 where the number of unshielded wires is U and the number of shielded cables is S. These card groups must follow the main program, function subprograms and subroutines in the order shown in Table 1. The data entries on the cards are either in Integer (I) format, e.g., 35, or in Exponential (E) format, e.g., 12.6E-3. All data entries must be right-justified in the assigned card column block. These data entries are printed out by the program. It is highly recommended that the user check this printout of input data to insure that the input data are as intended.

In the main program, the user must appropriately dimension all arrays for each problem. Comment cards are provided at the beginning of the main program to assist the user in providing proper dimensions.

Program SHIELD considers a transmission line consisting of U unshielded wires and S shielded cables and an associated reference conductor. The reference conductor type is determined by:

TYPE = 1: The reference conductor is a ground plane.

TYPE = 2: The reference conductor is an overall, circuiar, cylindrical shield.

Cross-sectional views of these two structures are shown in Fig. 4-1 and Fig. 4-2.

4.1 Transmission Line Characterization Cards, Group I

The purpose of this group is to define the type of reference conductor, the total line length, the number of unshielded wires and the number of

TABLE 1

Card Group Organization Data

(Note: the card groups must be arranged in the following order.)

	Card Group	Table
1) Line Characterization	I	2
2) Unshielded Wires (Omit if no unshielded wires)		
Wire 1	II	3
Wire 2	II	3
⋮	⋮	⋮
Wire U	II	3
3) Shielded Cables (Omit if no shielded cables)		
Cable 1	III(a)	4
	III(b)	5
	III(c)	6
Cable 2	III(a)	4
	III(b)	5
	III(c)	6
⋮	⋮	
Cable S	III(a)	4
	III(b)	5
	III(c)	6

TABLE 1 (Cont'd)

	Card Group	Table
4) Terminal Constraints		
(a) Unshielded Wires (Omit if no unshielded wires)		
Wire 1	IV(a)	7
Wire 2	IV(a)	7
⋮	⋮	
Wire U	IV(a)	7
(b) Shielded Cables (Omit if no shielded cables)		
Cable 1	IV(b)	8
Cable 2	IV(b)	8
⋮	⋮	
Cable S	IV(b)	8
(c) Mutual Admittances		
(See Table 9 for order information)	IV(c)	9
5) Frequency and Reference Conductor Impedance		
frequency 1	V	10
frequency 2	V	10
⋮	⋮	

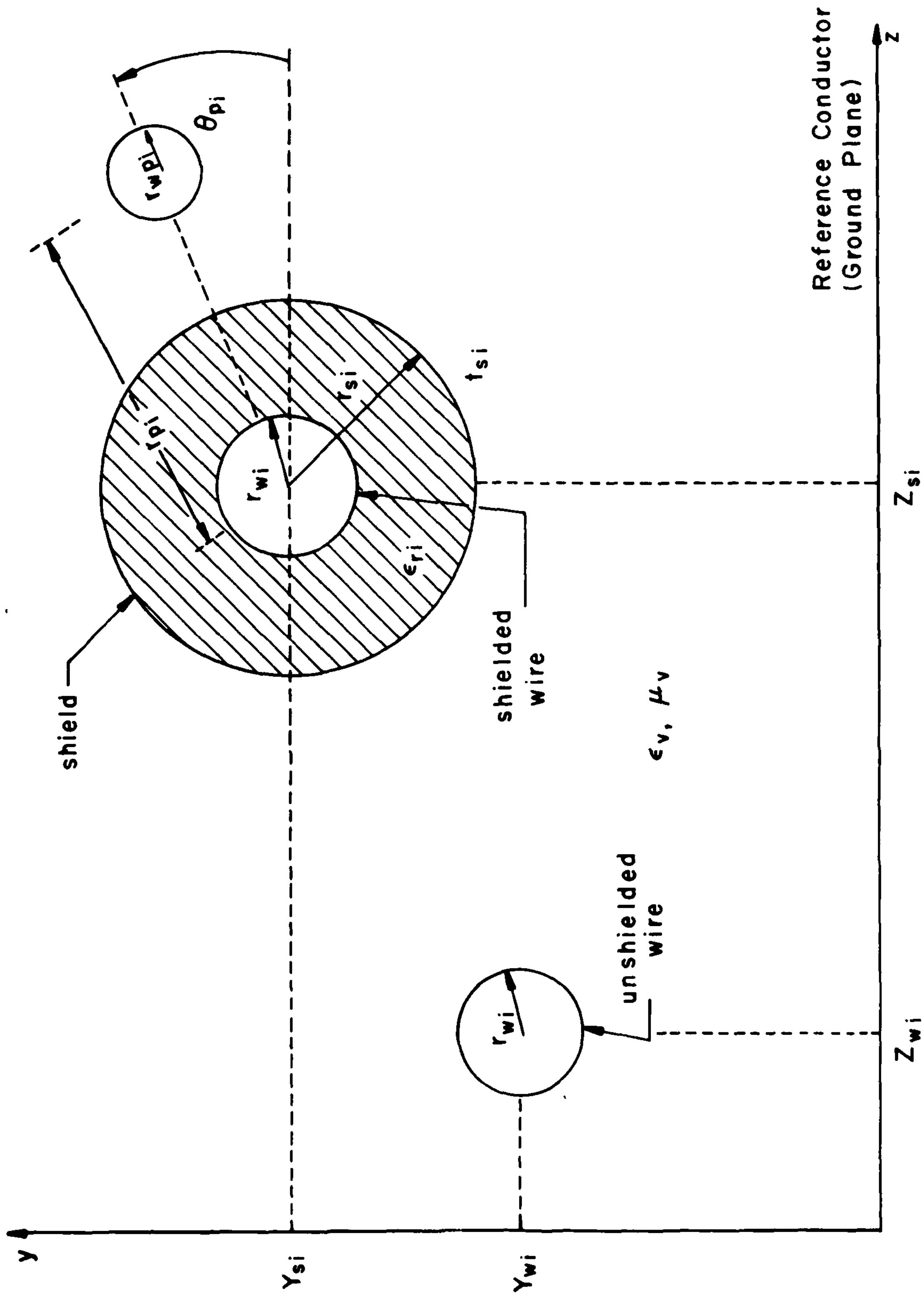


Figure 4-1. The TYPE 1 structure.

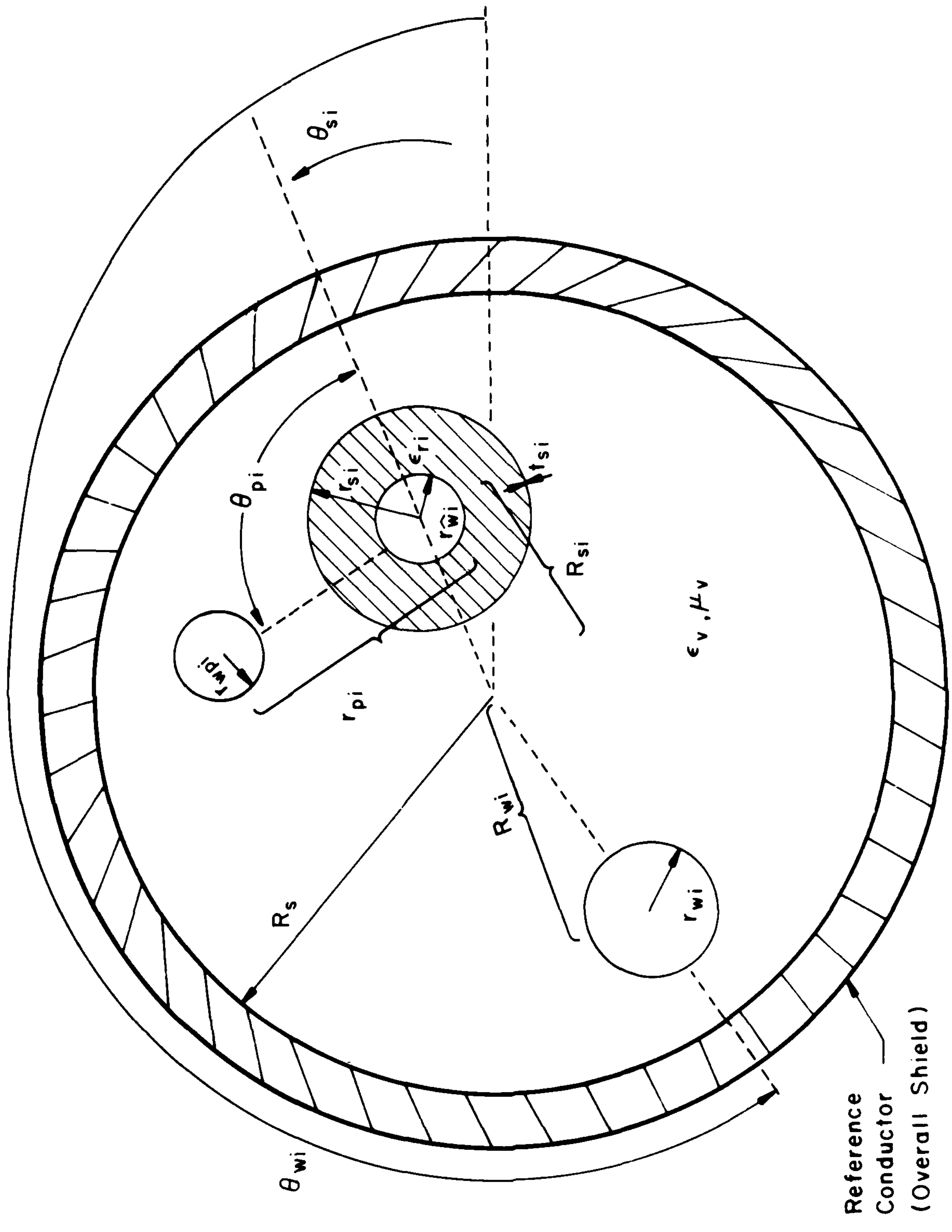


Figure 4-2. The TYPE 2 structure.

shielded wires. In addition, if the reference conductor is an overall, circular, cylindrical shield (TYPE 2) as shown in Fig. 4-2, then the interior radius of this shield, R_s is defined.

The format of these cards and their order is shown in Table 2.

4.2 Unshielded Wire Characteristics Cards, Group II

The purpose of this card group is to define the relative positions and the characteristics of the U unshielded wires. The format and order of these cards is shown in Table 3.

4.3 Shielded Cable Characteristics Cards, Group III(a)

The purpose of these cards is to define the relative positions and the characteristics of the shielded cable shields and the characteristics of their shielded wires. The format and ordering of these cards is given in Table 4.

4.4 Pigtail Wire Characteristics Cards, Groups III(b) and III(c)

The purpose of these groups is to define the relative locations and the characteristics of the pigtail wires. The cards for the pigtails at the left ($x = 0$) end are Group III(b), and their format and ordering are given in Table 5. The similar cards for the pigtails at the right ($x = \mathcal{L}$) end are Group III(c) and are described in Table 6.

The angular positions of the pigtail wires are measured in the counter-clockwise direction when looking from $x=0$ towards $x=\mathcal{L}$.

4.5 The Terminal Characteristics Cards, Group IV

The general structure of the terminal networks is illustrated in Fig. 2-5. At $x=0$ and $x=\mathcal{L}$ an admittance in parallel with a current source is connected between each unshielded wire and the reference conductor and between each shielded wire and the reference conductor. Card Group IV(a) (Table 7) defines these for the unshielded wires, and Card Group IV(b) (Table 8) defines these

TABLE 2

Format of the Line Characterization Cards, Group I

	Card Column	Format
Card #1		
TYPE (1,2)	1	I
Card #2		
$\mathcal{L}$ (total line length in meters)	1-10	E
Card #3		
U (number of unshielded wires)	1-2	I
Card #4		
S (number of shielded cables)	1-2	I
Card #5 (Omit if TYPE=1)		
R_s (interior radius of overall shield for TYPE 2 structures in meters)	11-20	E

TABLE 3

Format of the Unshielded Wire Characteristics Cards, Group II

(Omit if no unshielded wires)

		Card Column	Format
Card #1			
(a)	w_i (wire number)	1-2	I
	TYPE=1:		
(b)	Y_{wi} (height of wire above ground in meters)	11-20	E
(c)	Z_{wi} (horizontal coordinate of wire in meters)	31-40	E
	TYPE=2:		
(b)	R_{wi} (radial distance of wire from axis of overall shield in meters)	11-20	E
(c)	Θ_{wi} (angular position of wires in degrees)	31-40	
Card #2			
(a)	r_{wi} (radius of wire in mils)	11-20	E
(b)	(number of strands)	34-35	I
(c)	(radius of strands in mils)	51-60	E
(d)	(conductivity of strands relative to copper)	71-80	E

TABLE 4

Format of the Shielded Cable Characteristics Cards, Group III(a)

(Omit if no shielded cables)

	Card Column	Format
Card #1		
(a) s_i (shielded cable number)	1-2	I
(b) (shield type: 1(solid), 2(braided))	10	I
TYPE=1:		
(c) Y_{si} (height of shield above ground in meters)	21-30	E
(d) Z_{si} (horizontal coordinate of shield in meters)	41-50	E
TYPE=2:		
(c) R_{si} (radial distance of shield from axis of overall shield in meters)	21-30	E
(d) Θ_{si} (angular position of shield in degrees)	41-50	E
Card #2		
(a) r_{si} (interior radius of shield in meters)	11-20	E
(b) ε_{ri} (relative permittivity of dielectric)	21-30	E
(c) $r_{\hat{w}i}$ (radius of shielded wire in mils)	31-40	E
(d) (number of strands in shielded wire)	55-56	I
(e) (radius of strands in shielded wire in mils)	61-70	E
(f) (conductivity of shielded wire strands relative to copper)	71-80	E
Card #3		
Solid Shields:		
(a) t_{si} (shield thickness in mils)	11-20	E

TABLE 4 (Continued)

		Card Column	Format
Card #3 (Cont'd)			
(b)	(conductivity of shield relative to copper)	21-30	E
Braided Shields:			
(a)	(radius of braid wires in mils)	11-20	E
(b)	(conductivity of braid wires relative to copper)	21-30	E
(c)	(weave angle of braid in degrees)	31-40	E
(d)	(number of belts in braid)	44-45	I
(e)	(number of wires per belt)	54-55	I

TABLE 5

Format of Pigtail Wire Characteristics Cards for

Pigtail Wires at Left (x=0) End, Group III(b)

(Omit if no shielded cables)

	Card Column	Format
Card #1		
(a) $\mathcal{L}_{pi}$ (length of pigtail wire in meters)	11-20	E
(b) r_{pi} (radial separation of pigtail wire from axis of shielded cable in meters)	21-30	E
(c) Θ_{pi} (angular position of pigtail wire in degrees when looking from x=0 towards $x=\mathcal{L}$)	31-40	E
Card #2		
(a) r_{wpi} (radius of pigtail wire in mils)	11-20	E
(b) (number of strands in pigtail wire)	24-25	I
(c) (radius of strands in pigtail wire in mils)	31-40	E
(d) (conductivity of pigtail wire strands relative to copper)	41-50	E

Note: The pigtail wires may be of zero length in which case the other parameters must be nonzero.

TABLE 6

Format of Pigtail Wire Characteristics Cards for

Pigtail Wires at Right ($x=\ell$) End, Group III(c)

(Omit if no shielded cables)

Same as for Group III(b)

TABLE 7

Format of Terminal Characteristics Cards, Group IV

Self Terms for Unshielded Wires, Group IV(a)

(Omit if no unshielded wires)

Card #1

			Card Column	Format
(a)	I_{SOi} (current source between unshielded wire and reference conductor at x=0 in amps)	real part	1-10	E
		imaginary part	11-20	E
(b)	Y_{Oii} (admittance between unshielded wire and reference conductor at x=0 in Siemens)	real part	21-30	E
		imaginary part	31-40	E
(c)	$I_{S\ell i}$ (current source between unshielded wire and reference conductor at $x=\ell$ in amps)	real part	41-50	E
		imaginary part	51-60	E
(d)	$Y_{\ell ii}$ (admittance between unshielded wire and reference conductor at $x=\ell$ in Siemens)	real part	61-70	E
		imaginary part	71-80	E

TABLE 8

Format of Terminal Characteristics Cards, Group IV

Self Terms for Shielded Wires, Group IV(b)

(Omit if no shielded cables)

			Card Column	Format
Card #1				
(a)	I_{SOi} (current source between shielded wire and reference conductor at x=0 in amps)	real part	1-10	E
		imaginary part	11-20	E
(b)	Y_{0ii} (admittance between shielded wire and reference conductor at x=0 in Siemens)	real part	21-30	E
		imaginary part	31-40	E
(c)	$I_{S\ell i}$ (current source between shielded wire and reference conductor at $x=\ell$ in amps)	real part	41-50	E
		imaginary part	51-60	E
(d)	$Y_{\ell ii}$ (admittance between shielded wire and reference conductor at $x=\ell$ in Siemens)	real part	61-70	E
		imaginary part	71-80	E
Card #2				
(a)	IGNDL (grounding code for left end: 1 = short, 2 = open)		10	I
(b)	IGNDR (grounding code for right end: 1 = short, 2 = open)		40	I

TABLE 9

Format of Terminal Characteristics Cards, Group IV

Mutual Admittances Group IV(c)

Card #1

			Card Column	Format
(a)	Y_{Oij} (admittance between conductor i and conductor j at x=0)	real part	21-30	E
		imaginary part	31-40	E
(b)	$Y_{\ell ij}$ (admittance between conductor i and conductor j at x=ℓ)	real part	61-70	E
		imaginary part	71-80	E

Note: Cards must be arranged in order (w denotes unshieded wire and s denotes shielded wire) so as to fill the portion of the following matrix above the main diagonal <u>by rows</u>:

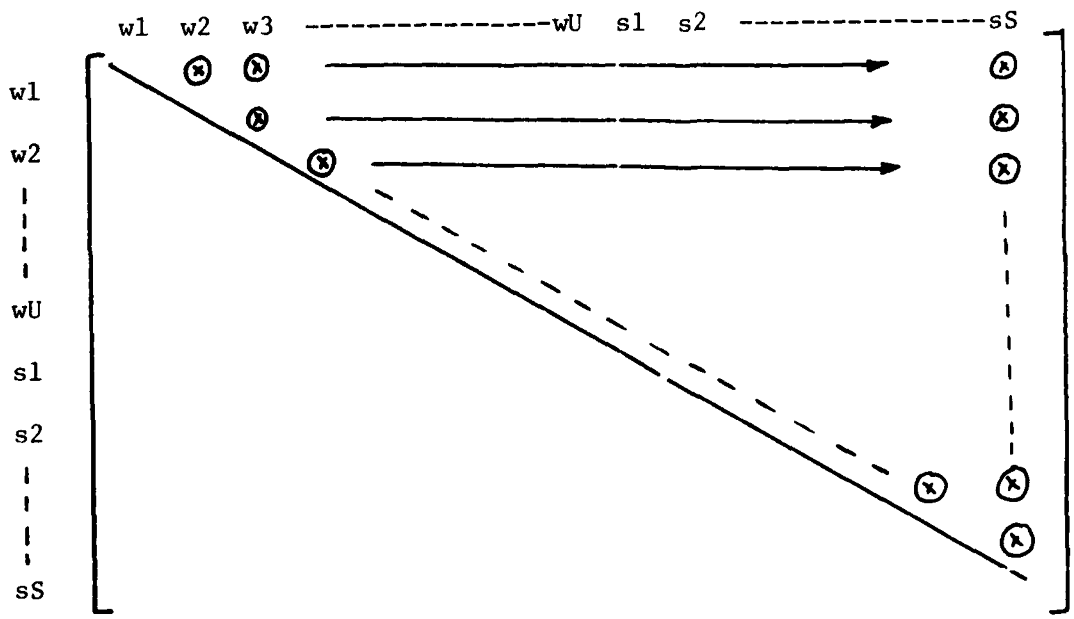


TABLE 9 (Continued)

Thus the cards are arranged sequentially in the order of the admittance connected between

w1 → w2, w3, -----, wU, s1, s2, -----, sS

w2 → w3, w4, -----, wU, s1, s2, -----, sS

⋮

w(U-1) → wU, s1, s2, ---, sS

wU → s1, s2, -----, sS

s1 → s2, s3, -----, sS

⋮

s(S-2) → s(S-1), sS

s(S-1) → sS

A total of

$$\frac{(U+S)\ (U+S-1)}{2}$$

cards are in this group

TABLE 10

Format of the Frequency and Reference Conductor Impedance

(Per-Unit-Length) Cards, Group V

		Card column	Format
Card #1			
F (frequency in Hz)		1-10	E
Card #2			
z_0 (reference conductor impedance per unit length in ohms/meter)	real part	1-10	E
	imaginary part	11-20	E

Note: Group V may be repeated at the end of the input deck in order for the program to analyze the structure for more than one frequency without having to redefine the previous structure and terminal data for each new frequency. However the previous data Groups I, II, III, IV are assumed to apply to all these frequencies.

for the shielded wires. The current sources at x=0 and x=$\mathcal{L}$ are directed from the reference conductor to the end of the wire. In addition, the grounding of the shields at x=0 and x=$\mathcal{L}$ are defined in Card Group IV(b) (Table 8). Each shield is connected via a pigtail wire (which may be of zero length) to the reference conductor by either a short circuit or an open circuit.

A mutual admittance (which may be zero, i.e., absent) is connected between the ends of all pairs of these wires. The format and ordering of these cards in Group IV(c) is given in Table 9. The user must be careful to adhere to the ordering of these cards as described in Table 9. The ordering scheme is very simple. First describe the admittances connecting unshielded wire #1 and all other wires sequentially in the order unshielded wires first and then the shielded wires. Next describe the admittances connecting unshielded wire #2 and all other wires sequentially in the order unshielded wires first and then the shielded wires. Continue in this fashion until the admittances connecting the last unshielded wire, wire #U, and all other wires (in this case only the shielded wires) have been described. Then describe the admittances connecting the first shielded wire and the remaining shielded wires, sequentially. Then describe the admittances connecting the second shielded wire and the remaining shielded wires, sequentially. Continue until the admittance connecting the next to last shielded wire (S-1) and the last shielded wire (S) is described and the process is complete. The total number of cards in this group is

$$\frac{(U+S)\ (U+S-1)}{2}$$

If the wires are numbered 1, 2, ---, U and the shielded wires are renumbered U+1, U+2, ---, U+S, then the ordering is

Y_{12}

Y_{13}

$\vdots$

$Y_{1\,(U+S)}$

Y_{23}

Y_{24}

$\vdots$

$Y_{2\,(U+S)}$

$\vdots$

$Y_{(U-1)\,U}$

$\vdots$

$Y_{(U-1)\,(U+S)}$

$Y_{U\,(U+1)}$

$\vdots$

$Y_{U\,(U+S)}$

$Y_{(U+1)\,(U+2)}$

$\vdots$

$Y_{(U+1)\,(U+S)}$

$\vdots$

$Y_{(U+S-1)\,(U+S)}$

4.6 The Frequency and Reference Conductor Impedance Cards, Group V

The final card group defines (1) the frequency for the analysis and (2) the per-unit-length impedance of the reference conductor at this frequency. This card group may be repeated at the end of the deck so that the program will analyze the structure at more than one frequency without the need to repeat the previous line and termination characterization groups. The program will process the data in Groups I, II, III and IV and compute the terminal voltages at the frequency on the first frequency card it encounters. It will then recompute the line response at each frequency on the remaining frequency cards (and use the reference conductor impedance on the following card). The program assumes that the data on card groups I, II, III, IV are to be used for all the remaining frequencies. If this is not intended by the user, in particular if the terminal characterizations are frequency dependent, then one may only run the program for one frequency. This feature, however, can be quite useful. If the termination networks are purely resistive, i.e., frequency independent over the frequency range of interest, then one may use as many repetitions of this group as desired and the program will compute the terminal responses at each frequency without the necessity for the user to input the data in Groups I, II, III, IV for each frequency.

4.7 Range of the Values of the Input Data

The only restrictions on the values of the input data are that only certain input parameters can be input as zero values. These are:

(1) NU (the number of unshielded wires)

or

NS (the number of shielded wires)

(Note: if NU=0 or NS=0 certain arrays must be dimensioned of size 1 not size 0. See cards SHLD0085 and SHLD0097.)

(2) Y_{wi} or Z_{wi} and Θ_{wi} in Table 3. (Note: No two wire locations may be the same, i.e., (Y_{wi},Z_{wi}) and $Y_{wj},Z_{wj})$ or (R_{wi},Θ_{wi}) and (R_{wj},Θ_{wj}).

(3) Y_{si} or Z_{si} and Θ_{si} in Table 4. (Note: No two shield locations may be the same. i.e., (Y_{si},Z_{si}) and (Y_{sj},Z_{sj}) or (R_{si},Θ_{si}) and (R_{sj},Θ_{sj}).)

(4) ℓ_{pi} (The pigtail lengths for left or right or both pigtails. See Table 5 and Table 6).

(5) Θ_{pi} (The angular positions of the pigtail wires. See Tables 5 and Table 6.)

(6) Any of the terminal current source or admittance values. (see Table 7, Table 8 and Table 9.)

(7) z_0 (The reference conductor impedance at a frequency. See Table 10.)

All of the other data entries should be nonzero (and represent realistic values).

V. Program Checkout

In order to check the proper functioning of the program, several examples were run. Examples consisting of 2 unshielded wires and no shielded wires were run for TYPE 1 and TYPE 2 structures. The outputs of SHIELD were compared to those of program XTALK2 described in [27] and were found to be identical as they should be since XTALK2 performs the same calculations for unshielded wires as does SHIELD. SHIELD was also run for 2 shielded wires each having 8cm pigtail sections on both ends and separated by 1.5cm and 1.5cm above ground. These data were measured experimentally and reported in [1]. In addition a computer program was written for [1] in a "brute force" manner to show predictions of these experimental data. Those predictions are reported in [1]. SHIELD was run for this configuration and the predictions compared favorably with the experimental data in [1] and compared almost exactly with predictions given in [1] by the "brute force" program.

As an integrated test, we performed an experiment to illustrate the prediction accuracies of SHIELD. The experimental configuration is shown in Fig. 5-1. Photographs of the experimental setup are given in Fig. 5-2. The unshielded wires are #22 gauge stranded (radius = 15 mils) with 7 strands of #30 gauge wire (radius = 5 mils). The insulation is pvc (neglected by the program). The shielded cables are identical to those used in [1]. They are braided with inner shield radius of 35 mils = 8.89E-4 m and an inner, shielded wire which is #22 gauge (radius = 15 mils) composed of 7 strands of #30 gauge wire (radius = 5 mils). The inner dielectric is teflon with $\varepsilon_r = 2.1$. The braid wires have radii of 2.5 mils, and the braid consists of 16 belts with 4 wires per belt and a weave angle of 30 degrees. The pigtail wires are #20 gauge (radius = 16 mils) solid bare copper wires. A listing of the input

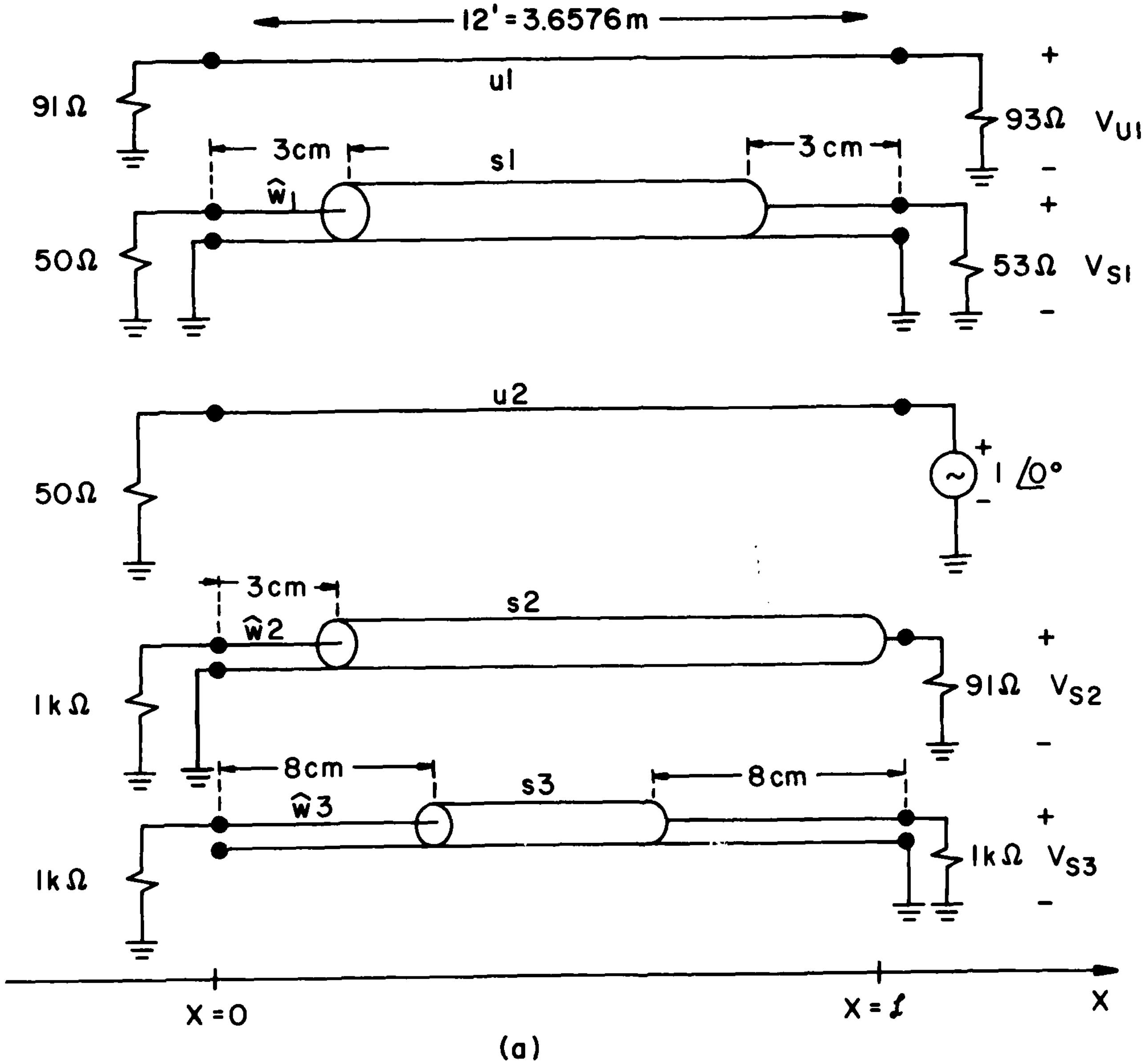


Figure 5-1. The experimental configuration.

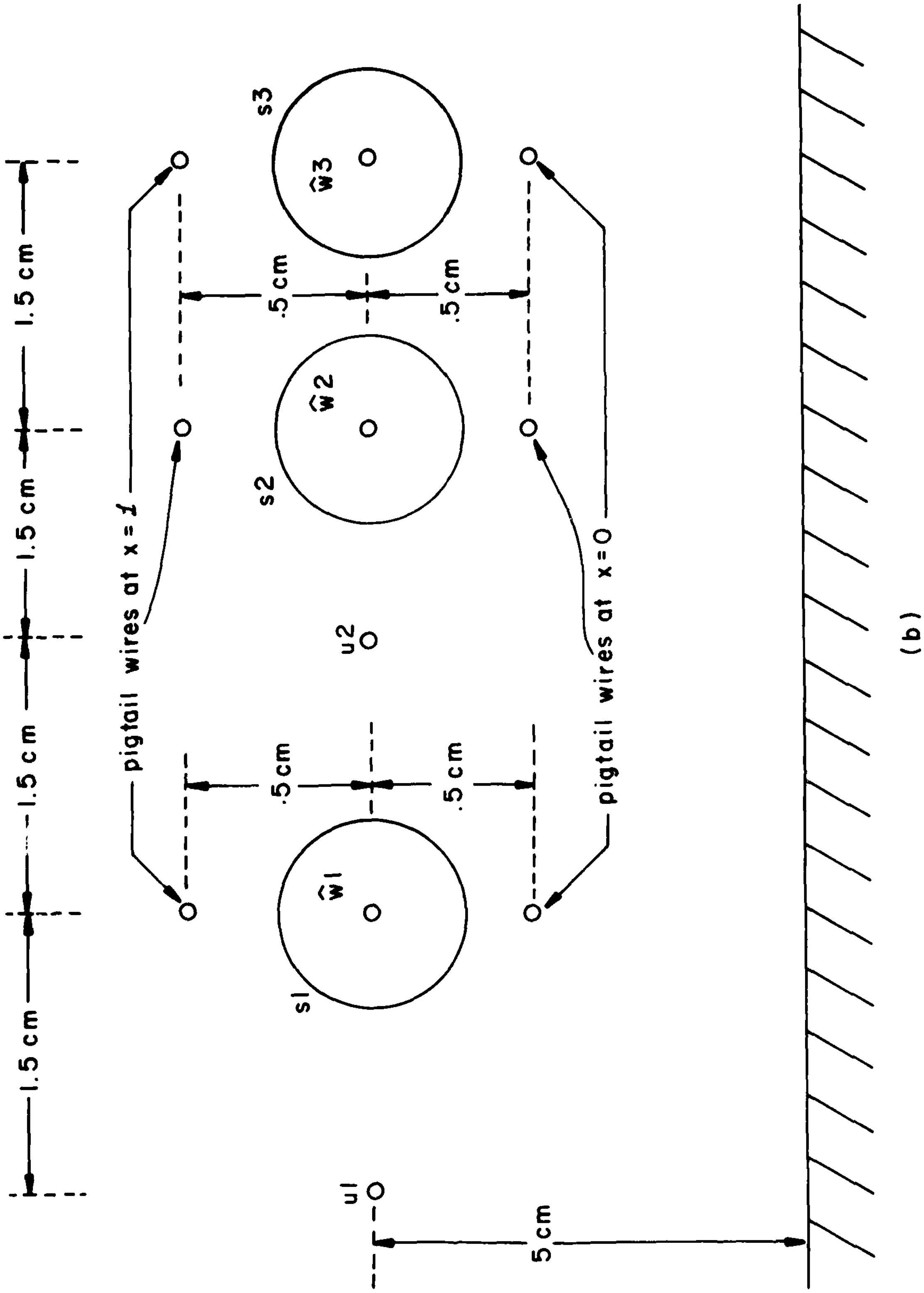


Figure 5-1 (Cont'd)... The experimental configuration.

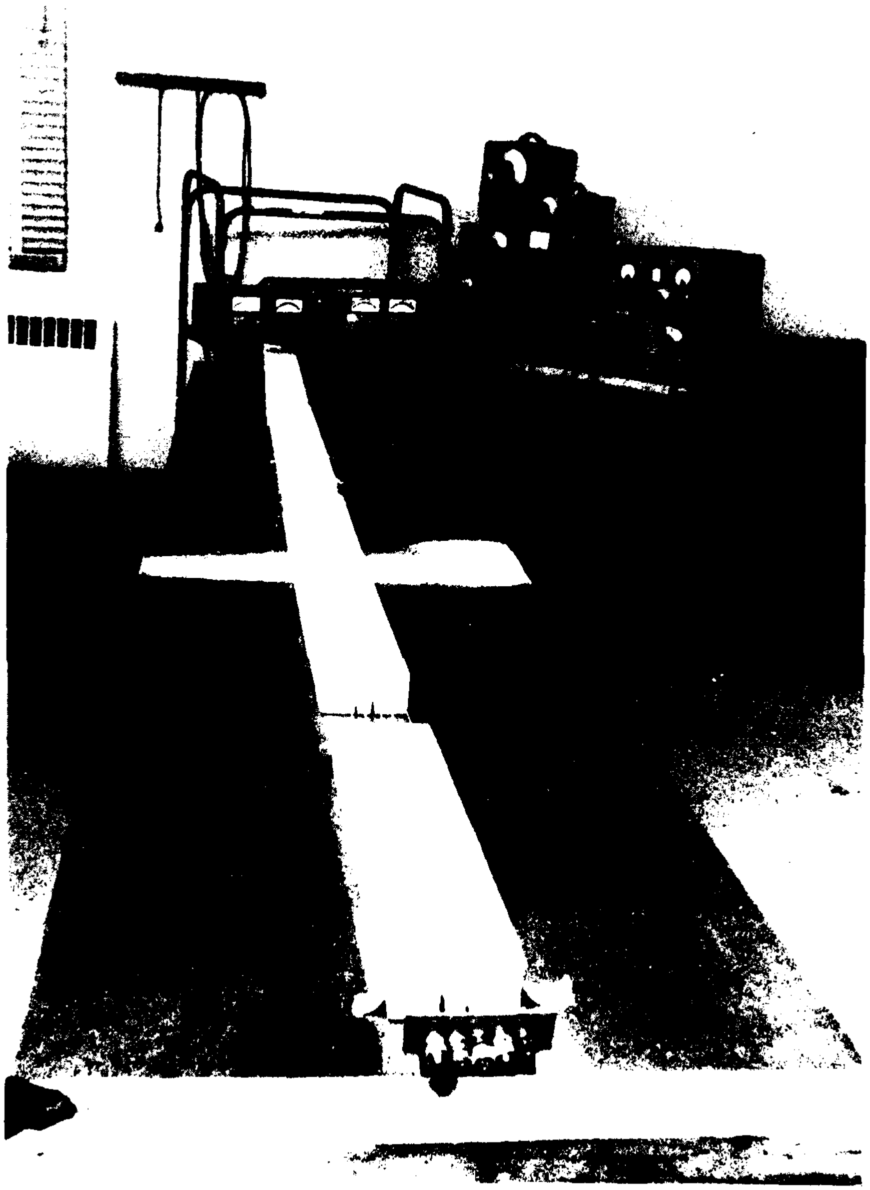


Figure 5-2. Photographs of the experimental setup.

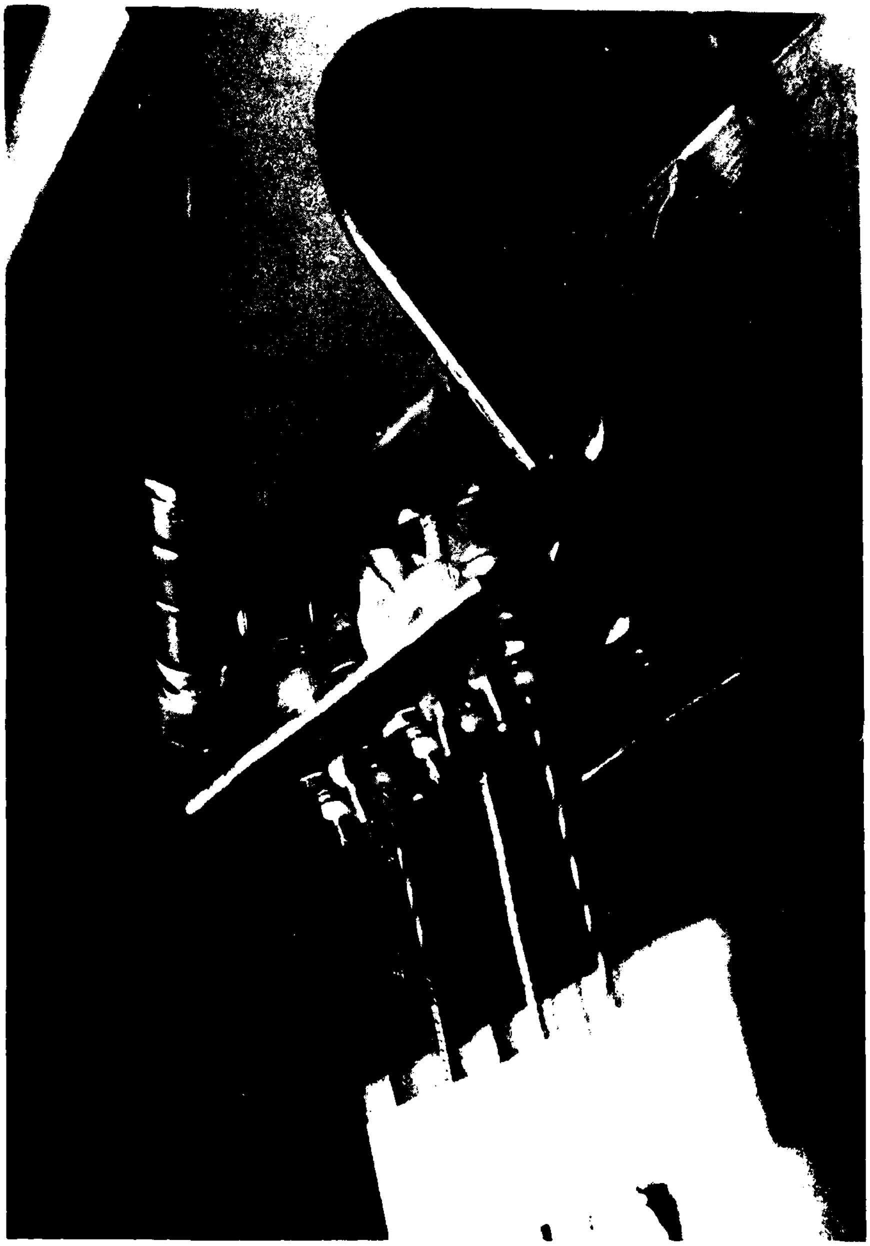


Figure 5-2 (Cont'd)... Photographs of the experimental setup.

data is given in Fig. 5-3. A sample printout of some of the results for 100kHz → 900kHz is given in Fig. 5-4.

The unshielded wires, shielded cables and shielded wires are numbered in Fig. 5-1 as u1, u2, s1, s2, s3, $\hat{w}1$, $\hat{w}2$, $\hat{w}3$. In the experiment, an oscillator was attached to the right end of the second unshielded wire (u2), and the voltage of the oscillator was increased until the input voltage to that line was 1 volt. Then the voltages coupled to the other ends of the other wires u1, $\hat{w}1$, $\hat{w}2$, $\hat{w}3$ were measured resulting in voltage transfer ratios. A zero source impedance source is not allowed in the SHIELD input data. Thus to simulate this situation, the source at the right end of the second unshielded wire is 50V with source resistance of 50Ω or, equivalently, a 1A source in parallel with a resistance of 50Ω (2.0E-2 Siemens admittance). (See the listing in Fig. 5-3.) Once SHIELD was run for this configuration, the voltage transfer ratios corresponding to the experimental data are obtained by dividing the voltages at the ends of each line by the voltage at the right end of the second unshielded wire.

The voltage transfer ratios (magnitude and angle) predicted by SHIELD and experimentally measured at the right end ($x = \mathcal{L}$) of each line are shown in Fig. 5-5 through Fig. 5-8. Fig. 5-5(a) and Fig. 5-5(b) show the magnitude and angle, respectively, of the measured voltage at the right end of the first unshielded wire, V_{u1}, versus the predicted voltage transfer ratio of SHIELD:

$$\frac{V_{w1}(\mathcal{L})}{V_{w2}(\mathcal{L})}$$

The predictions are quite good and well within 1dB below 10 MHz. Above 10 MHz the line is becoming electrically long, and, consequently, rapid variations in both the magnitude and the phase of the voltage transfer ratio are observed.

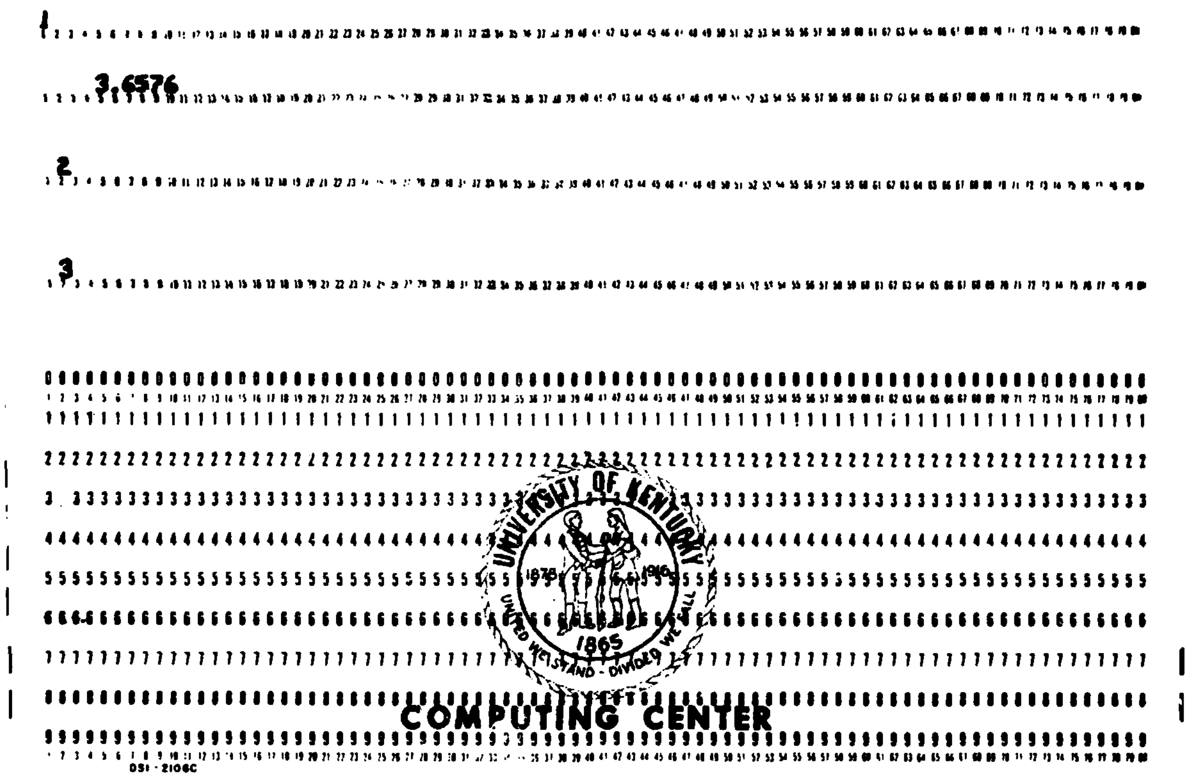


Figure 5-3. Input data for the experiment-line structure characterization data.

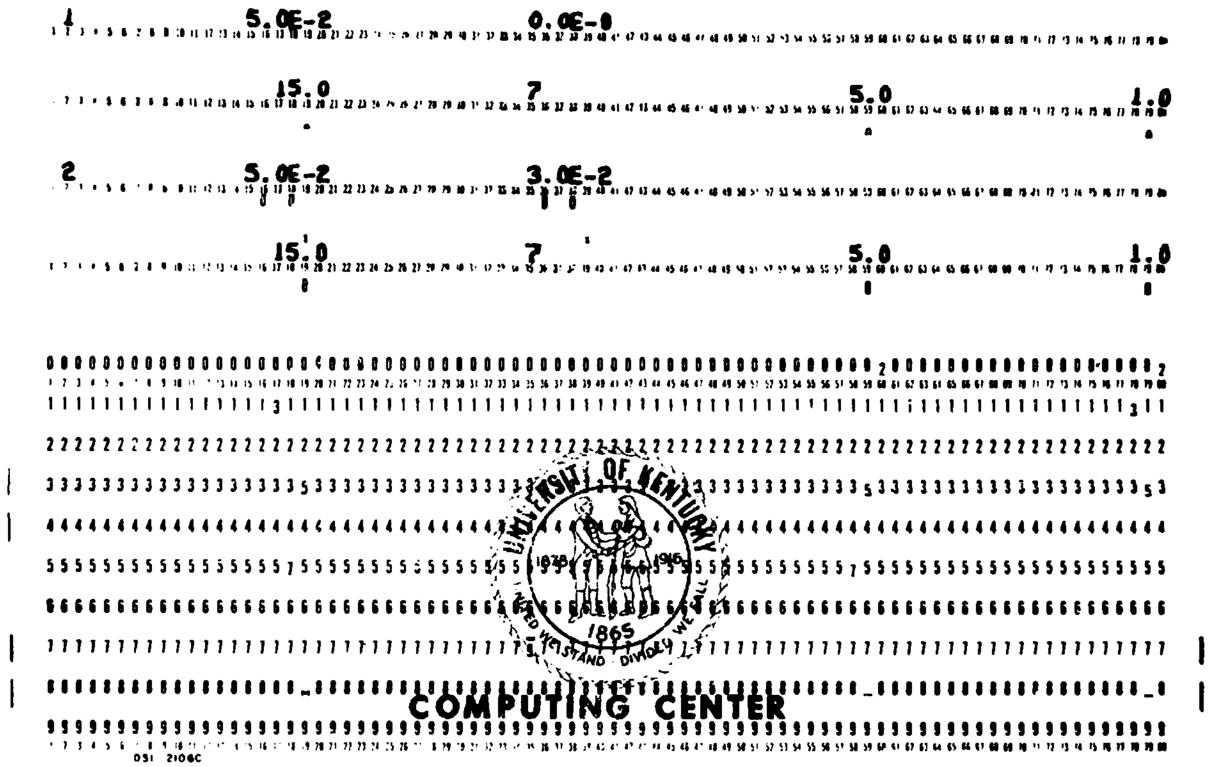


Figure 5-3 (Cont'd)... Input data for the experiment-unshielded wire data.

```
1       2              5.0E-2                  1.5E-2
          8.89E-4        2.1      15.0                  7             5.0      1.0
             2.5         1.0      30.0    16           4
          3.0E-2     5.0E-3      270.0
             16.0    1             16.0         1.0
          3.0E-2     5.0E-3       90.0
             16.0    1             16.0         1.0
2       2              5.0E-2                  4.5E-2
          8.89E-4        2.1      15.0                  7             5.0      1.0
             2.5         1.0      30.0    16           4
          3.0E-2     5.0E-3      270.0
             16.0    1             16.0         1.0
          0.0E-0     5.0E-3       90.0
             16.0    1             16.0         1.0
3       2              5.0E-2                  6.0E-2
          8.89E-4        2.1      15.0                  7             5.0      1.0
             2.5         1.0      30.0    16           4
          8.0E-2     5.0E-3      270.0
             16.0    1             16.0         1.0
          8.0E-2     5.0E-3       90.0
             16.0    1             16.0         1.0
```

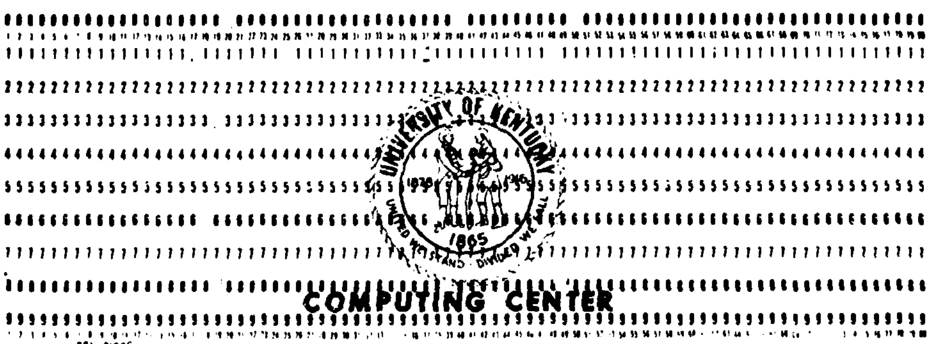


Figure 5-3 (Cont'd)... Input data for the experimental-shielded cable data.

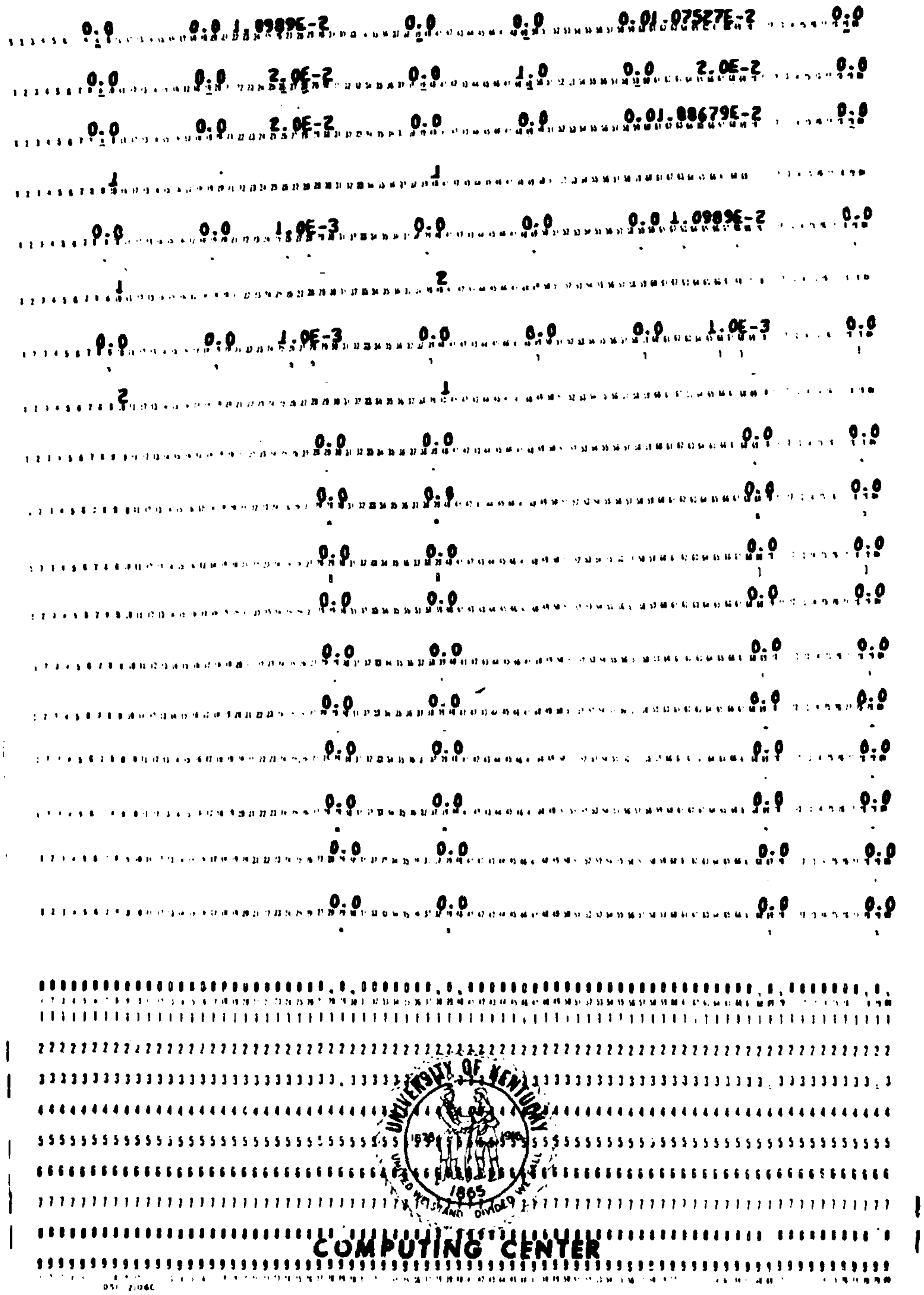


Figure 5-3 (Cont'd)... Input data for the experiment-terminal characterization data.

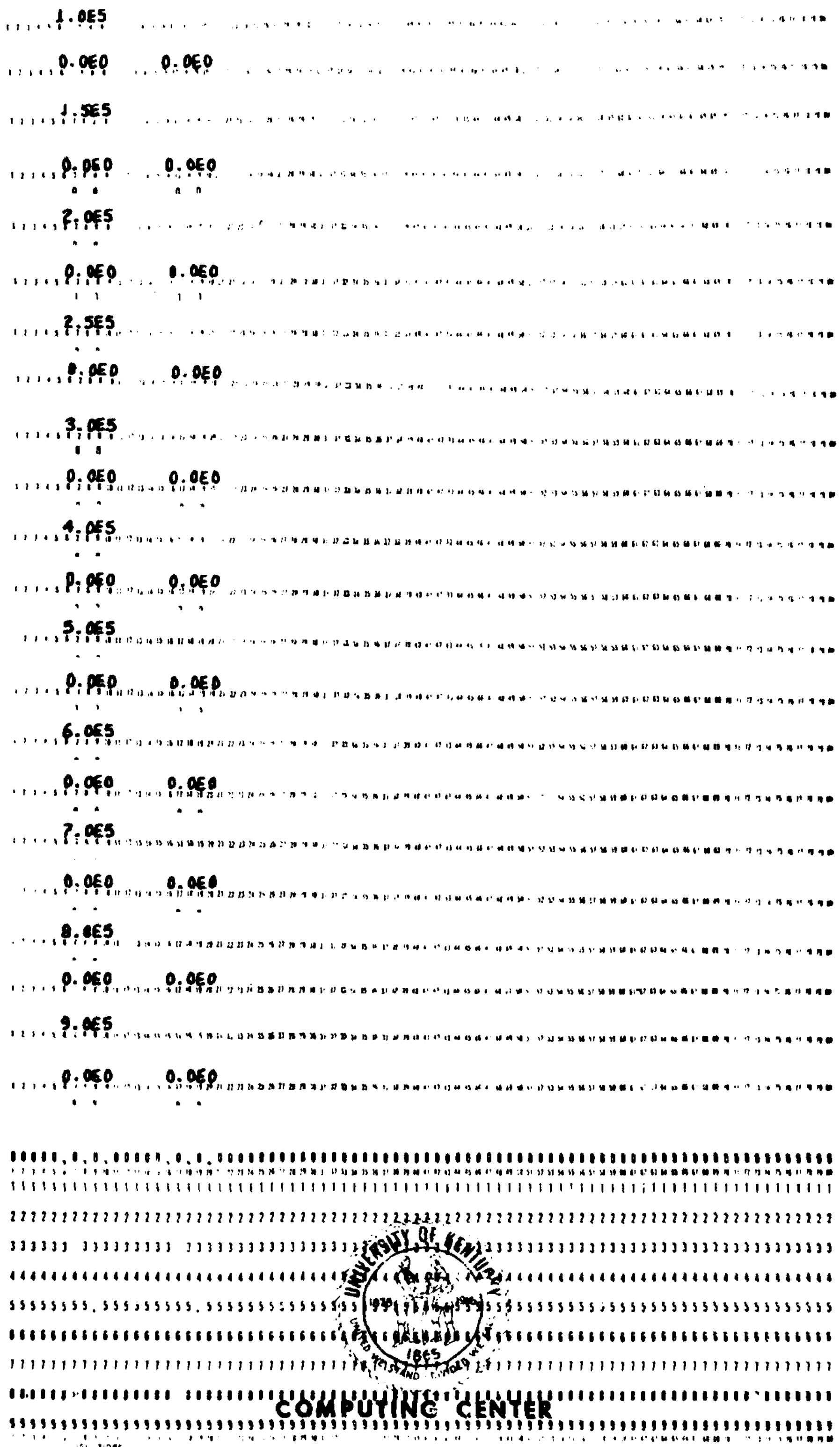


Figure 5-3 (Cont'd)... Input data for the experiment-frequency and common impedance data.

```
                         PROGRAM SHIELD

                       2 UNSHIELDED WIRES
                        3 SHIELDED WIRES
               LINE LENGTH (METERS)=   3.658D 00

            REFERENCE CONDUCTOR IS A GROUND PLANE

                 DATA FOR THE UNSHIELDED WIRES

YW= WIRE HEIGHT ABOVE GROUND (METERS) OR RADIAL DISTANCE FROM CENTER OF SHIELD (METERS)
ZW= HORIZONTAL COORDINATE (METERS) OR ANGULAR POSITION (DEGREES)
RW= WIRE RADIUS (MILS)
NWST= NUMBER OF WIRE STRANDS
RWST= RADIUS OF WIRE STRANDS (MILS)
SIGWST= CONDUCTIVITY OF WIRE STRANDS (RELATIVE TO COPPER)

WIRE     YW            ZW            RW         NWST    RWST          SIGWST

  1    5.0000D-02    0.0000D-01    1.5000 01     7    5.0000 00     1.0000 00
  2    5.0000D-02    3.0000D-02    1.5000 01     7    5.0000 00     1.0000 00

                  DATA FOR THE SHIELDED WIRES

YS= SHIELD HEIGHT ABOVE GROUND (METERS) OR RADIAL DISTANCE FROM CENTER OF SHIELD (METERS)
ZS= HORIZONTAL COORDINATE (METERS) OR ANGULAR POSITION (DEGREES)
RS= INTERIOR SHIELD RADIUS (METERS)
ERS= RELATIVE PERMITTIVITY OF INTERIOR DIELECTRIC
RW= SHIELDED WIRE RADIUS (MILS)
NWST= NUMBER OF SHIELDED WIRE STRANDS
RWST= RADIUS OF SHIELDED WIRE STRANDS (MILS)
SIGWST= CONDUCTIVITY OF SHIELDED WIRE STRANDS (RELATIVE TO COPPER)
```

Figure 5-4. Printout of computed results for the experiment.

SHIELD	YS	ZS	RS	ERS	RW	NWST	RWST	SIGWST
1	5.0000-02	1.5000-02	8.890D-04	2.1000 00	1.5000 01	7	5.0000 00	1.0000 00
2	5.0000-02	4.5000-02	8.890D-04	2.1000 00	1.5000 01	7	5.0000 00	1.0000 00
3	5.0000-02	6.0000-02	8.890D-04	2.100D 00	1.500D 01	7	5.0000 00	1.0000 00

SHIELD CHARACTERISTICS

TS= SOLID SHIELD THICKNESS (MILS)
SIGS= SOLID SHIELD CONDUCTIVITY (RELATIVE TO COPPER)
RB= RADIUS OF BRAID WIRES (MILS)
SIGB= BRAID WIRE CONDUCTIVITY (RELATIVE TO COPPER)
THB= BRAID WEAVE ANGLE (DEGREES)
BELTS= NUMBER OF BELTS IN BRAID
WPB= NUMBER OF WIRES PER BELT

SHIELD	TYPE	TS	SIGS	RB	SIGB	THB	BELTS	WPB
1	BRAIDED			2.500D 00	1.0000 00	3.000D 01	16	4
2	BRAIDED			2.500D 00	1.000D 00	3.000D 01	16	4
3	BRAIDED			2.5000 00	1.0000 00	3.0000 01	16	4

DATA FOR THE PIGTAILS

LEFT PIGTAILS

LPL= LENGTH OF LEFT PIGTAIL (METERS)
RPL= RADIAL SEPARATION OF PIGTAIL WIRE FROM SHIELDED WIRE (METERS)
THPL= ANGULAR POSITION OF PIGTAIL WIRE (DEGREES)
RPWL= RADIUS OF PIGTAIL WIRE (MILS)
NPL= NUMBER OF STRANDS IN PIGTAIL WIRE
RPWSTL= RADIUS OF PIGTAIL WIRE STRANDS (MILS)
SIGPWL= CONDUCTIVITY OF PIGTAIL WIRE STRANDS (RELATIVE TO COPPER)

SHIELD	LPL	RPL	THPL	RPWL	NPL	RPWSTL	SIGPWL
1	3.000D-02	5.000D-03	2.700D 02	1.6000 01	1	1.6000 01	1.000D 00
2	3.000D-02	5.000D-03	2.700D 02	1.6000 01	1	1.6000 01	1.0000 00
3	8.000D-02	5.000D-03	2.700D 02	1.6000 01	1	1.600D 01	1.000D 00

RIGHT PIGTAILS

Figure 5-4 (Cont'd)... Printout of computed results for the experiment.

```
LPR= LENGTH OF RIGHT PIGTAIL (METERS)
RPR= RADIAL SEPARATION OF PIGTAIL WIRE FROM SHIELDED WIRE (METERS)
THPR= ANGULAR POSITION OF PIGTAIL WIRE (DEGREES)
RPWR= RADIUS OF PIGTAIL WIRE (MILS)
NPR= NUMBER OF STRANDS IN PIGTAIL WIRE
RPWSTR= RADIUS OF PIGTAIL WIRE STRANDS (MILS)
SIGPWR= CONDUCTIVITY OF PIGTAIL WIRE STRANDS RELATIVE TO COPPER)
```

SHIELD	LPR	RPR	THPR	RPWR	NPR	RPWSTR	SIGPWR
1	3.0000D-02	5.0000D-03	9.0000D 01	1.6000D 01	1	1.6000D 01	1.0000D 00
2	0.0000D-01	5.0000D-03	9.0000D 01	1.6000D 01	1	1.6000D 01	1.0000D 00
3	8.0000D-02	5.0000D-03	9.0000D 01	1.6000D 01	1	1.6000D 01	1.0000D 00

TERMINAL SOURCE AND IMPEDANCE DATA

```
IOR= REAL PART OF CURRENT SOURCE BETWEEN WIRE AND REFERENCE CONDUCTOR AT X=0
IOI= IMAG PART OF CURRENT SOURCE BETWEEN WIRE AND REFERENCE CONDUCTOR AT X=0
YOR= REAL PART OF ADMITTANCE BETWEEN WIRE AND REFERENCE CONDUCTOR AT X=0
YOI= IMAG PART OF ADMITTANCE BETWEEN WIRE AND REFERENCE CONDUCTOR AT X=0
ILR= REAL PART OF CURRENT SOURCE BETWEEN WIRE AND REFERENCE CONDUCTOR AT X=L
ILI= IMAG PART OF CURRENT SOURCE BETWEEN WIRE AND REFERENCE CONDUCTOR AT X=L
YLR= REAL PART OF ADMITTANCE BETWEEN WIRE AND REFERENCE CONDUCTOR AT X=L
YLI= IMAG PART OF ADMITTANCE BETWEEN WIRE AND REFERENCE CONDUCTOR AT X=L
```

WIRE	IOR	IOI	YOR	YOI	ILR	ILI	YLR	YLI
1	0.0000D-01	0.0000D-01	1.099D-02	0.0000D-01	0.0000D-01	0.0000D-01	1.075D-02	0.0000D-01
2	0.0000D-01	0.0000D-01	2.0000D-02	0.0000D-01	1.0000D 00	0.0000D-01	2.0000D-02	0.0000D-01

SHIELDED WIRE	IOR	IOI	YOR	YOI	ILR	ILI	YLR	YLI
1	0.0000D-01	0.0000D-01	2.0000D-02	0.0000D-01	0.0000D-01	0.0000D-01	1.887D-02	0.0000D-01
2	0.0000D-01	0.0000D-01	1.0000D-03	0.0000D-01	0.0000D-01	0.0000D-01	1.099D-02	0.0000D-01
3	0.0000D-01	0.0000D-01	1.0000D-03	0.0000D-01	0.0000D-01	0.0000D-01	1.0000D-03	0.0000D-01

IMPEDANCES BETWEEN WIRES

WIRE	WIRE	YOR	YOI	YLR	YLI
1	2	0.0000D-01	0.0000D-01	0.0000D-01	0.0000D-01

Figure 5-4 (Cont'd)... Printout of computed results for the experiment.

WIRE	SHIELDED WIRE	YOR	YOI	YLR	YLR
1	1	0.0000D-01	0.0000D-01	0.0000D-01	0.0000D-01
1	2	0.0000D-01	0.0000D-01	0.0000D-01	0.0000D-01
1	3	0.0000D-01	0.0000D-01	0.0000D-01	0.0000D-01
2	1	0.0000D-01	0.0000D-01	0.0000D-01	0.0000D-01
2	2	0.0000D-01	0.0000D-01	0.0000D-01	0.0000D-01
2	3	0.0000D-01	0.0000D-01	0.0000D-01	0.0000D-01

SHIELDED WIRE	SHIELDED WIRE	YOR	YOI	YLR	YLI
1	2	0.0000D-01	0.0000D-01	0.0000D-01	0.0000D-01
1	3	0.0000D-01	0.0000D-01	0.0000D-01	0.0000D-01
2	3	0.0000D-01	0.0000D-01	0.0000D-01	0.0000D-01

SHIELD TERMINATION DATA

SHIELD	TERMINATION AT X=0	TERMINATION AT X=L
1	SHORT	SHORT
2	SHORT	OPEN
3	OPEN	SHORT

FREQUENCY(HZ)= 1.0000D 05

REFERENCE CONDUCTOR IMPEDANCE= 0.0000D-01 +J 0.0000D-01 OHMS PER METER

THE NUMBER OF RIGHT PIGTAIL SECTIONS = 2

THE NUMBER OF LEFT PIGTAIL SECTIONS = 2

WIRE	VOM(VOLTS)	VOA(DEGREES)	VLM(VOLTS)	VLA(DEGREES)
1	4.9930-02	-9.646D 01	5.567D-02	8.408D 01
2	2.4950 01	-1.3090 00	2.507D 01	1.217D 00

Figure 5-4 (Cont'd)... Printout of computed results for the experiment.

SHIELDED WIRE	VOM(VOLTS)	VOA(DEGREES)	VLM(VOLTS)	VLA(DEGREES)
1	9.047D-03	-1.719D 02	9.602D-03	8.556D 00
2	2.929D-01	-9.381D 01	2.799D-02	1.037D 02
3	1.036D-01	-8.480D 01	1.004D-01	7.891D 01

FREQUENCY(HZ)= 1.500D 05

REFERENCE CONDUCTOR IMPEDANCE= 0.0000D-01 +J 0.0000D-01 OHMS PER METER

THE NUMBER OF RIGHT PIGTAIL SECTIONS = 2

THE NUMBER OF LEFT PIGTAIL SECTIONS = 2

WIRE	VOM(VOLTS)	VOA(DEGREES)	VLM(VOLTS)	VLA(DEGREES)
1	7.461D-02	-9.606D 01	8.323D-02	8.445D 01
2	2.494D 01	-1.963D 00	2.509D 01	1.823D 00

SHIELDED WIRE	VOM(VOLTS)	VOA(DEGREES)	VLM(VOLTS)	VLA(DEGREES)
1	9.049D-03	-1.698D 02	9.616D-03	1.080D 01
2	4.392D-01	-9.496D 01	4.426D-02	1.103D 02
3	1.613D-01	-8.101D 01	1.485D-01	7.433D 01

FREQUENCY(HZ)= 2.000D 05

REFERENCE CONDUCTOR IMPEDANCE= 0.0000D-01 +J 0.0000D-01 OHMS PER METER

THE NUMBER OF RIGHT PIGTAIL SECTIONS = 2

THE NUMBER OF LEFT PIGTAIL SECTIONS = 2

Figure 5-4 (Cont'd)... Printout of computed results for the experiment.

WIRE	VOM(VOLTS)	VOA(DEGREES)	VLM(VOLTS)	VLA(DEGREES)
1	9.933D-02	-9.637D 01	1.108D-01	8.417D 01
2	2.493D 01	-2.617D 00	2.512D 01	2.426D 00

SHIELDED WIRE	VOM(VOLTS)	VOA(DEGREES)	VLM(VOLTS)	VLA(DEGREES)
1	9.042D-03	-1.673D 02	9.625D-03	1.354D 01
2	5.855D-01	-9.626D 01	6.304D-02	1.159D 02
3	2.249D-01	-7.881D 01	1.943D-01	6.972D 01

FREQUENCY(HZ)= 2.500D 05

REFERENCE CONDUCTOR IMPEDANCE= 0.033D-01 +J 0.0000D-01 OHMS PER METER

THE NUMBER OF RIGHT PIGTAIL SECTIONS = 2

THE NUMBER OF LEFT PIGTAIL SECTIONS = 2

WIRE	VOM(VOLTS)	VOA(DEGREES)	VLM(VOLTS)	VLA(DEGREES)
1	1.240D-01	-9.697D 01	1.304D-01	8.362D 01
2	2.492D 01	-3.270D 00	2.516D 01	3.025D 00

SHIELDED WIRE	VOM(VOLTS)	VOA(DEGREES)	VLM(VOLTS)	VLA(DEGREES)
1	9.034D-03	-1.645D 02	9.637D-03	1.646D 01
2	7.319D-01	-9.763D 01	8.485D-02	1.206D 02
3	2.951D-01	-7.738D 01	2.373D-01	6.520D 01

FREQUENCY(HZ)= 3.000D 05

REFERENCE CONDUCTOR IMPEDANCE= 0.000D-01 +J 0.000D-01 OHMS PER METER

Figure 5-4 (Cont'd)... Printout of computed results for the experiment.

THE NUMBER OF RIGHT PIGTAIL SECTIONS = 2

THE NUMBER OF LEFT PIGTAIL SECTIONS = 2

WIRE	VOM(VOLTS)	VOA(DEGREES)	VLM(VOLTS)	VLA(DEGREES)
1	1.487D-01	-9.772D 01	1.659D-01	8.294D 01
2	2.490D 01	-3.923D 00	2.521D 01	3.619D 00

SHIELDED WIRE	VOM(VOLTS)	VOA(DEGREES)	VLM(VOLTS)	VLA(DEGREES)
1	9.048D-03	-1.615D 02	9.677D-03	1.966D 01
2	8.783D-01	-9.903D 01	1.108D-01	1.244D 02
3	3.718D-01	-7.662D 01	2.773D-01	6.084D 01

FREQUENCY(HZ)= 4.000D 05

REFERENCE CONDUCTOR IMPEDANCE= 0.000D-01 +J 0.000D-01 OHMS PER METER

THE NUMBER OF RIGHT PIGTAIL SECTIONS = 2

THE NUMBER OF LEFT PIGTAIL SECTIONS = 2

WIRE	VOM(VOLTS)	VOA(DEGREES)	VLM(VOLTS)	VLA(DEGREES)
1	1.980D-01	-9.943D 01	2.208D-01	8.137D 01
2	2.486D 01	-5.225D 00	2.533D 01	4.787D 00

SHIELDED WIRE	VOM(VOLTS)	VOA(DEGREES)	VLM(VOLTS)	VLA(DEGREES)

Figure 5-4 (Cont'd)... Printout of computed results for the experiment.

1	9.155D-03	-1.547D 02	9.857D-03	2.669D 01
2	1.171D 00	-1.019D 02	1.715D-01	1.297D 02
3	5.427D-01	-7.660D 01	3.475D-01	5.268D 01

FREQUENCY(HZ)= 5.000D 05

REFERENCE CONDUCTOR IMPEDANCE= 0.0300-01 +J 0.0000-01 OHMS PER METER

THE NUMBER OF RIGHT PIGTAIL SECTIONS = 2

THE NUMBER OF LEFT PIGTAIL SECTIONS = 2

WIRE	VOM(VOLTS)	VOA(DEGREES)	VLM(VOLTS)	VLA(DEGREES)
1	2.471D-01	-1.013D 02	2.755D-01	7.966D 01
2	2.480D 01	-6.524D 00	2.549D 01	5.924D 00

SHIELDED WIRE	VOM(VOLTS)	VOA(DEGREES)	VLM(VOLTS)	VLA(DEGREES)
1	9.453D-03	-1.473D 02	1.026D-02	3.424D 01
2	1.464D 00	-1.048D 02	2.485D-01	1.328D 02
3	7.320D-01	-7.789D 01	4.053D-01	4.533D 01

FREQUENCY(HZ)= 6.000D 05

REFERENCE CONDUCTOR IMPEDANCE= 0.0300-01 +J 0.0000-01 OHMS PER METER

THE NUMBER OF RIGHT PIGTAIL SECTIONS = 2

THE NUMBER OF LEFT PIGTAIL SECTIONS = 2

Figure 5-4 (Cont'd)... Printout of computed results for the experiment.

WIRE	VOM(VOLTS)	VOA(DEGREES)	VLM(VOLTS)	VLA(DEGREES)
1	2.959D-01	-1.032D 02	3.299D-01	7.789D 01
2	2.474D 01	-7.817D 00	2.568D 01	7.023D 00

SHIELDED WIRE	VOM(VOLTS)	VOA(DEGREES)	VLM(VOLTS)	VLA(DEGREES)
1	1.003D-02	-1.397D 02	1.096D-02	4.169D 01
2	1.756D 00	-1.077D 02	3.417D-01	1.345D 02
3	9.337D-01	-7.991D 01	4.519D-01	3.875D 01

FREQUENCY(HZ)= 7.000D 05

REFERENCE CONDUCTOR IMPEDANCE= 0.0000-01 +J 0.000D-01 OHMS PER METER

THE NUMBER OF RIGHT PIGTAIL SECTIONS = 2

THE NUMBER OF LEFT PIGTAIL SECTIONS = 2

WIRE	VOM(VOLTS)	VOA(DEGREES)	VLM(VOLTS)	VLA(DEGREES)
1	3.445D-01	-1.052D 02	3.839D-01	7.608D 01
2	2.466D 01	-9.105D 00	2.590D 01	8.080D 00

SHIELDED WIRE	VOM(VOLTS)	VOA(DEGREES)	VLM(VOLTS)	VLA(DEGREES)
1	1.092D-02	-1.329D 02	1.200D-02	4.836D 01
2	2.049D 00	-1.106D 02	4.512D-01	1.350D 02
3	1.143D 00	-8.227D 01	4.895D-01	3.286D 01

FREQUENCY(HZ)= 8.000D 05

REFERENCE CONDUCTOR IMPEDANCE= 0.0000-01 +J 0.000D-01 OHMS PER METER

THE NUMBER OF RIGHT PIGTAIL SECTIONS = 2

Figure 5-4 (Cont'd)... Printout of computed results for the experiment.

THE NUMBER OF LEFT PIGTAIL SECTIONS = 2

WIRE	VOM(VOLTS)	VOA(DEGREES)	VLM(VOLTS)	VLA(DEGREES)
1	3.928D-01	-1.072D 02	4.374D-01	7.423D 01
2	2.457D 01	-1.839D 01	2.615D 01	9.089D 00

SHIELDED WIRE	VOM(VOLTS)	VOA(DEGREES)	VLM(VOLTS)	VLA(DEGREES)
1	1.211D-02	-1.271D 02	1.336D-02	5.385D 01
2	2.341D 00	-1.136D 02	5.778D-01	1.348D 02
3	1.358D 00	-8.478D 01	5.197D-01	2.756D 01

FREQUENCY(HZ)= 9.0000D 05

REFERENCE CONDUCTOR IMPEDANCE= 0.0000D-01 +J 0.0000D-01 OHMS PER METER

THE NUMBER OF RIGHT PIGTAIL SECTIONS = 2

THE NUMBER OF LEFT PIGTAIL SECTIONS = 2

WIRE	VOM(VOLTS)	VOA(DEGREES)	VLM(VOLTS)	VLA(DEGREES)
1	4.406D-01	-1.893D 02	4.904D-01	7.237D 01
2	2.447D 01	-1.166D 01	2.643D 01	1.005D 01

SHIELDED WIRE	VOM(VOLTS)	VOA(DEGREES)	VLM(VOLTS)	VLA(DEGREES)
1	1.357D-02	-1.227D 02	1.499D-02	5.801D 01
2	2.632D 00	-1.166D 02	7.192D-01	1.340D 02
3	1.575D 00	-8.734D 01	5.442D-01	2.277D 01

Figure 5-4 (Cont'd)... Printout of computed results for the experiment.

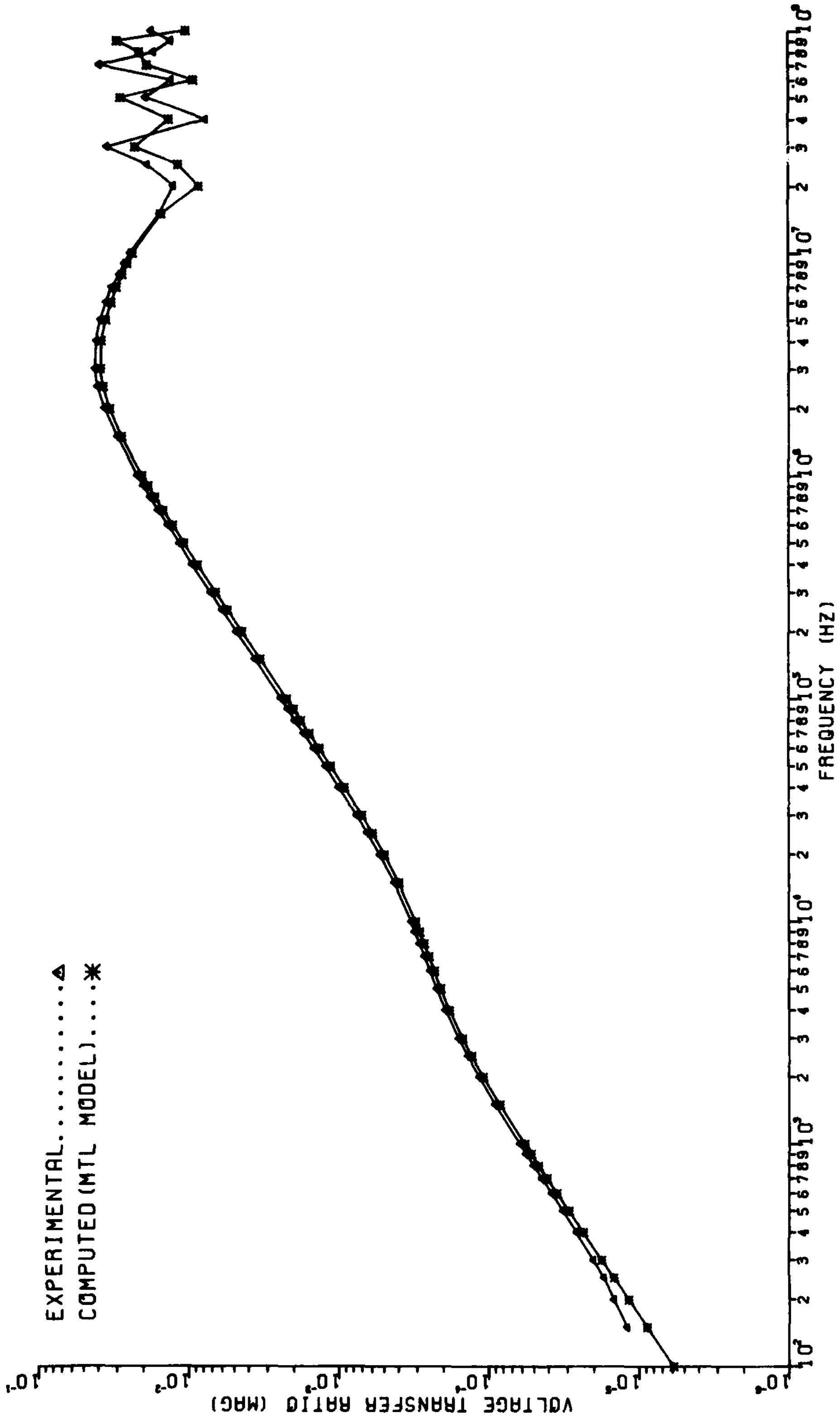


Figure 5-5(a). Magnitude of voltage transfer ratio to right end of ul.

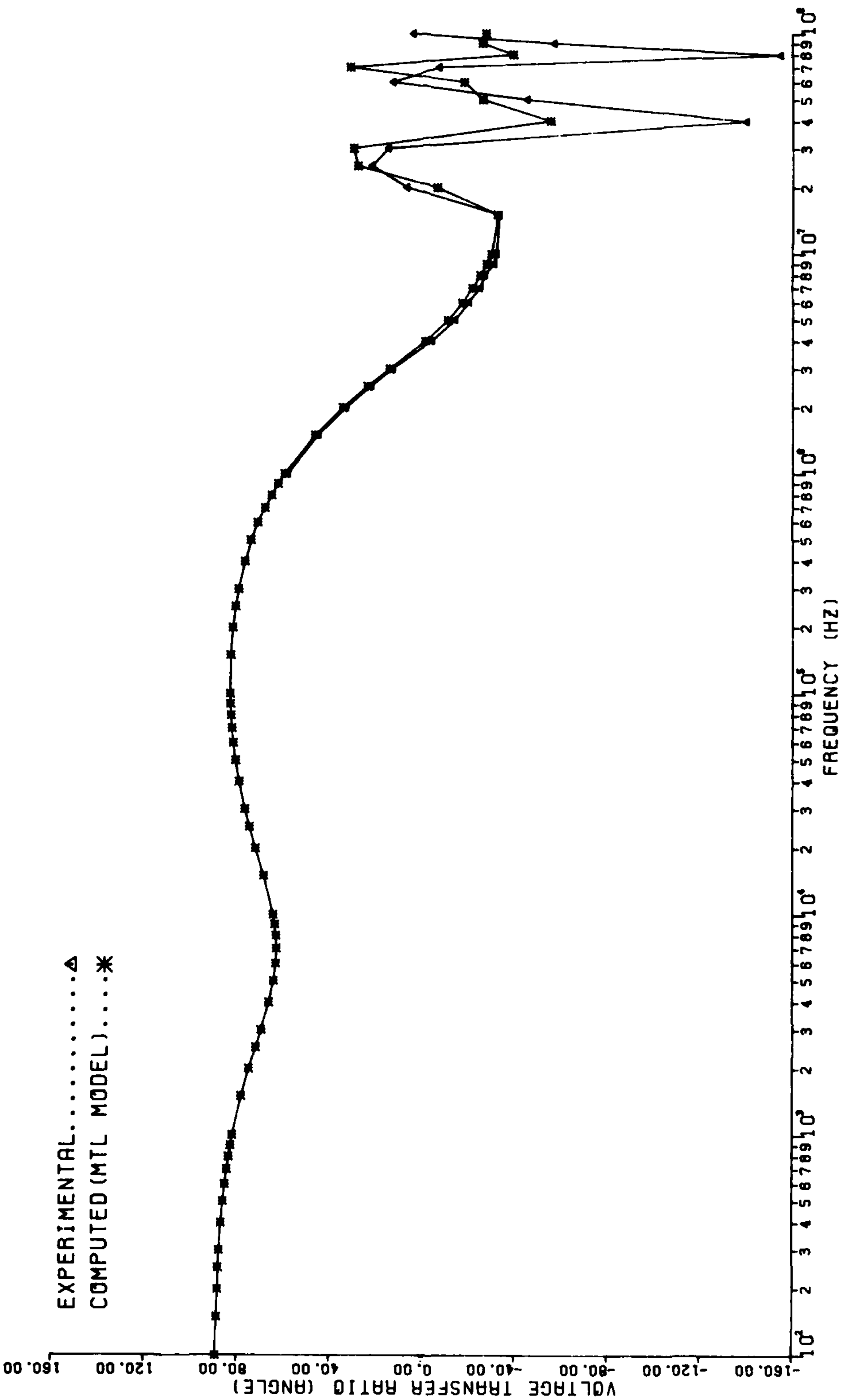


Figure 5-5(b). Angle of voltage transfer ratio to right end of ul.

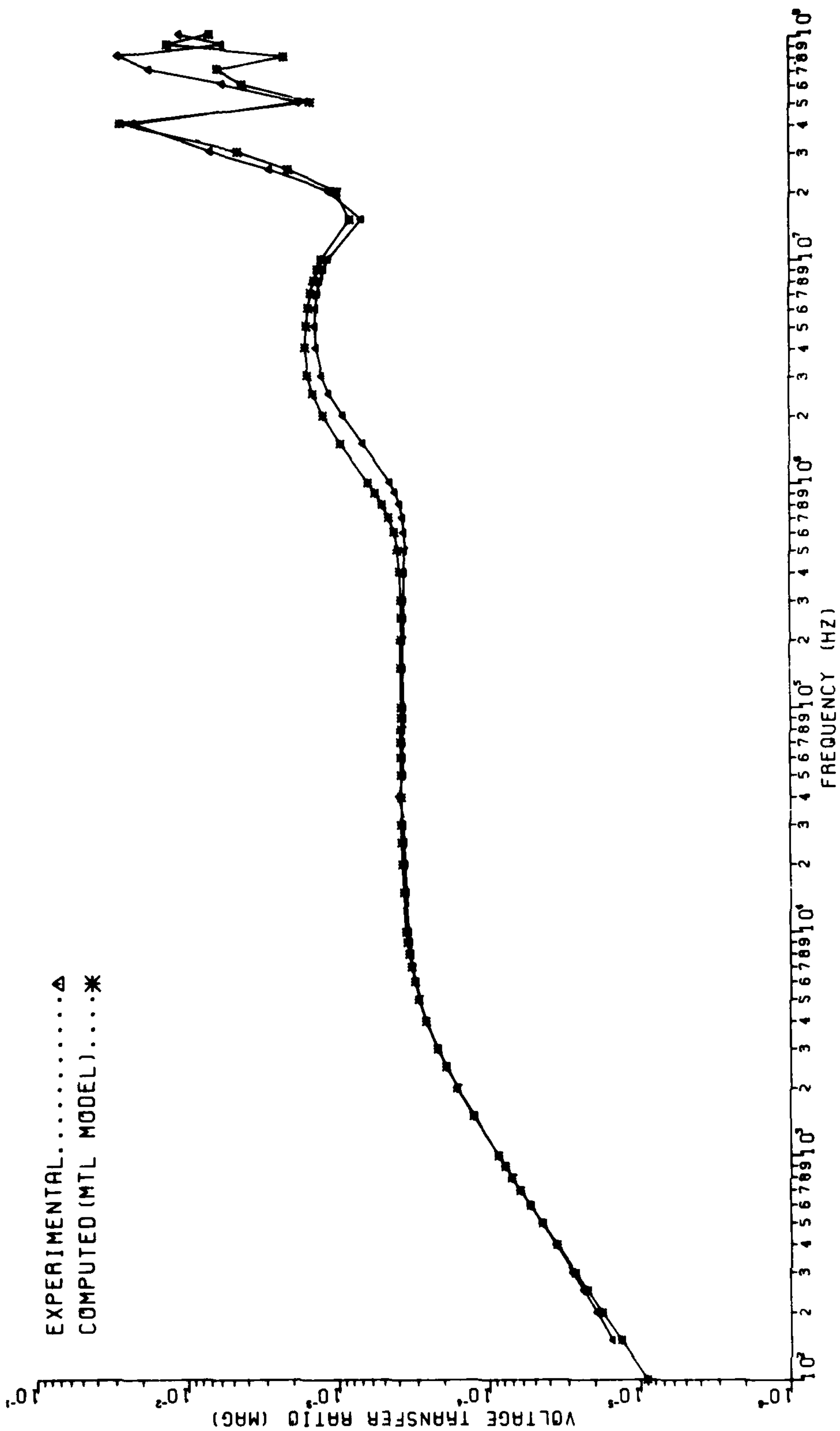


Figure 5-6(a). Magnitude of voltage transfer ratio to right end of sl, $\hat{w}1$.

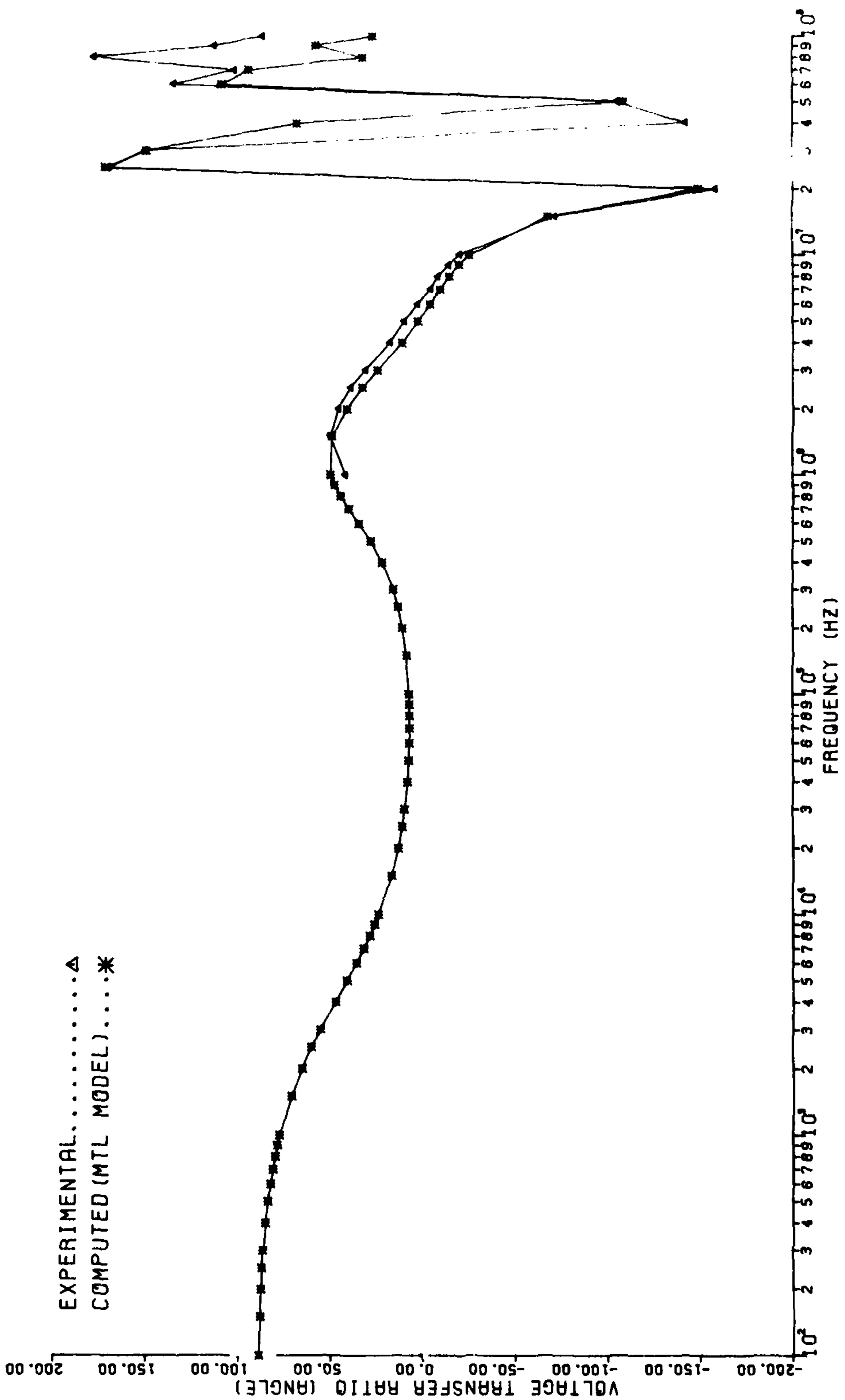


Figure 5-6(b). Angle of voltage transfer ratio to right end of sl, $\hat{w}1$.

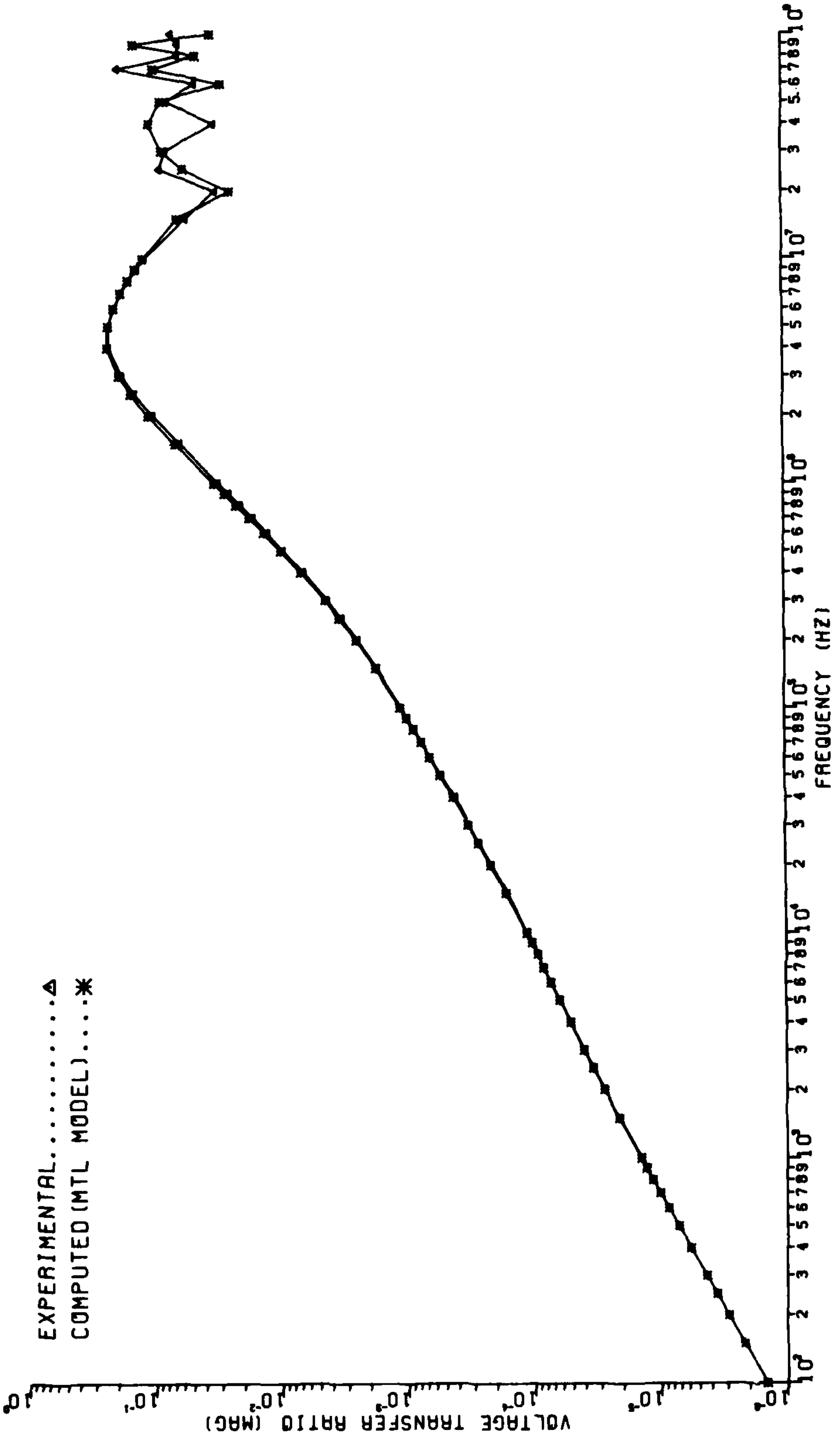


Figure 5-7(a). Magnitude of voltage transfer ratio to right end of s2, ŵ2.

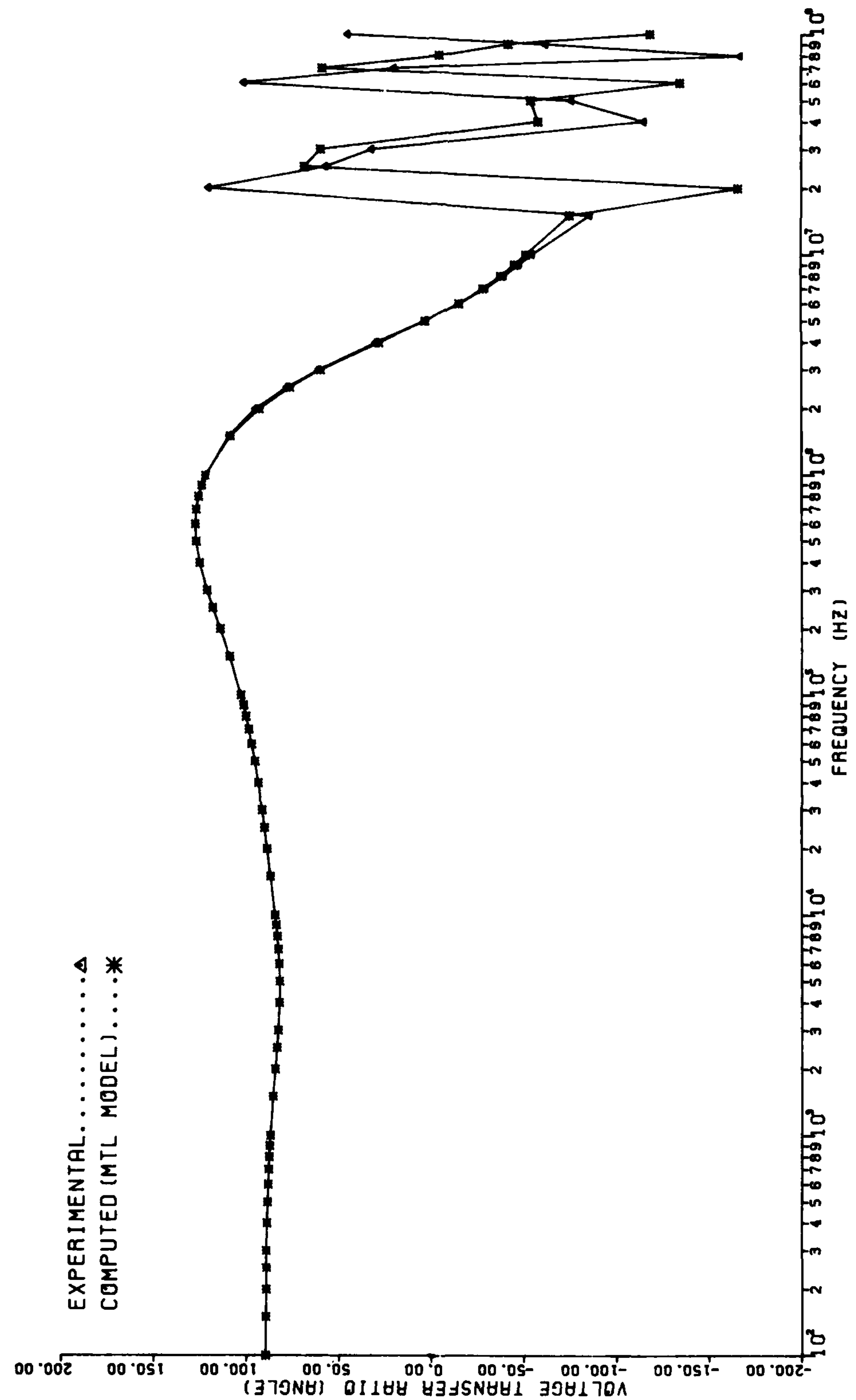


Figure 5-7(b). Angle of voltage transfer ratio to right end of s2, ŵ2.

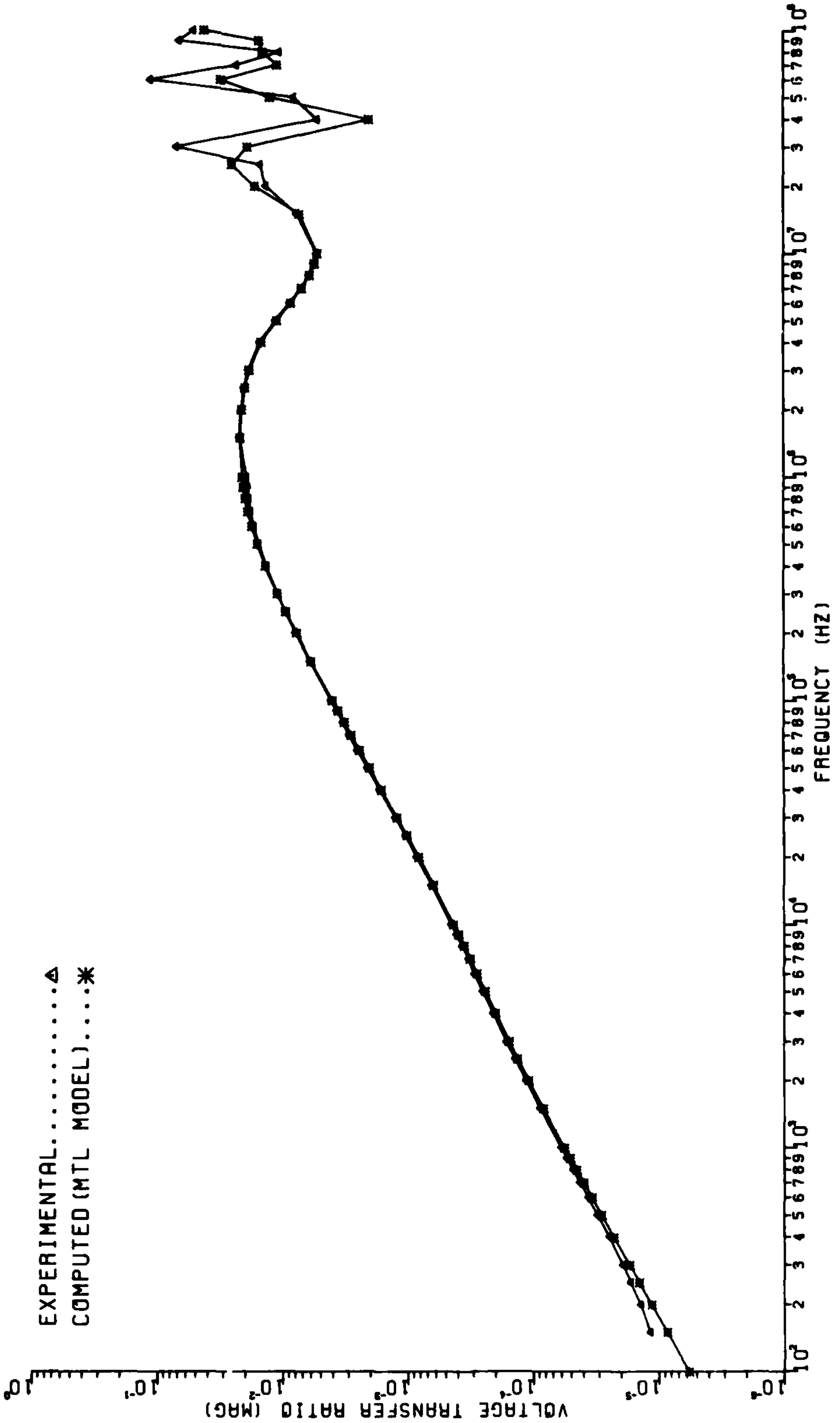


Figure 5-8(a). Magnitude of voltage transfer ratio to right end of s3, $\hat{w}3$.

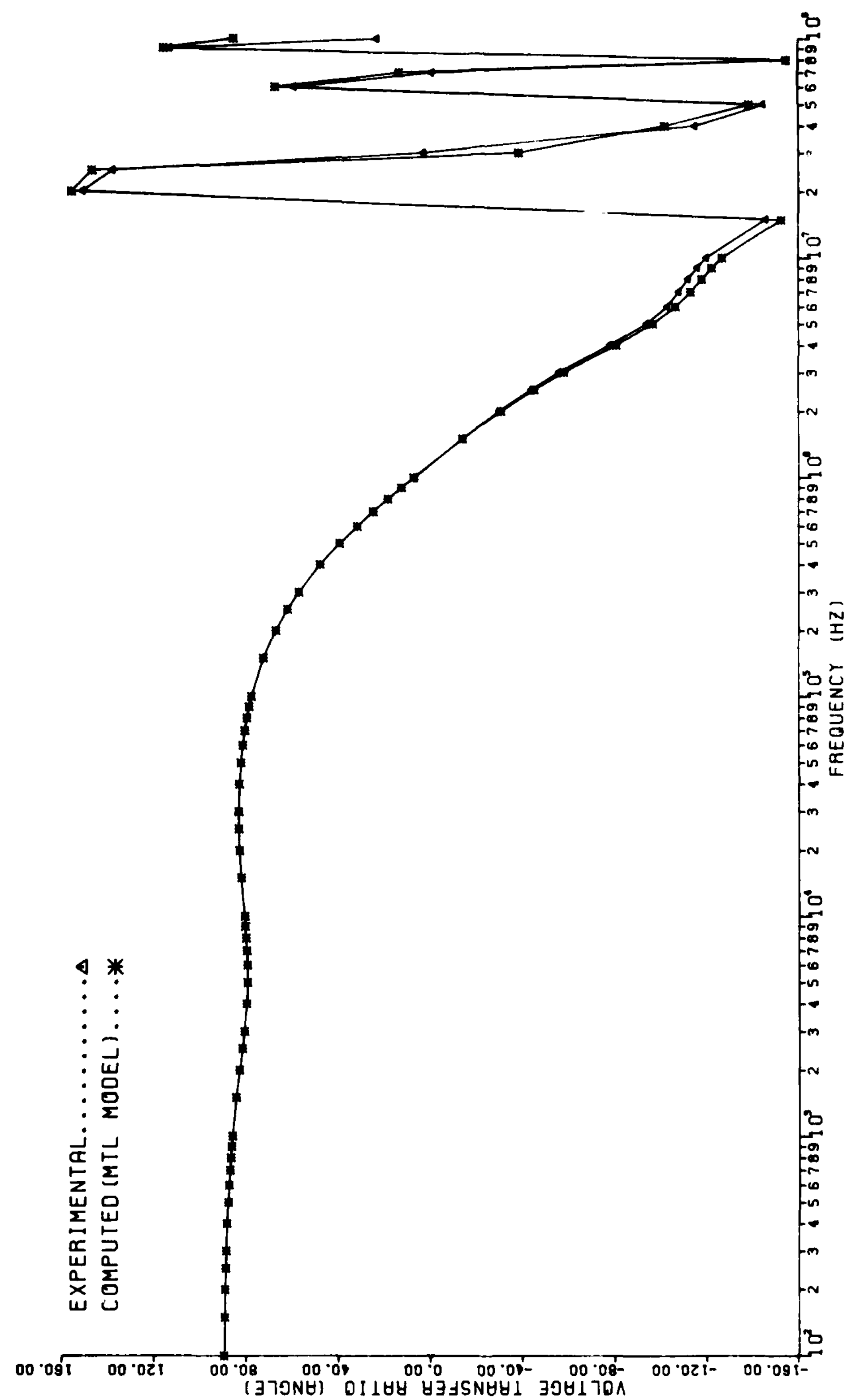


Figure 5-8(b). Angle of voltage transfer ratio to right end of s3, ŵ3.

Nevertheless, the program predicts these results rather well.

A similar comparison of the voltage transfer ratio to the right end of the first shielded wire, V_{s1}, and the predictions of SHIELD,

$$\frac{V_{\hat{w}1}(\mathcal{L})}{V_{w2}(\mathcal{L})}$$

are shown in Fig. 5-6. Note that above 1 MHz, the coupling which had become "flat" for lower frequencies tends to rise. This is a result of the coupling via the two 3cm pigtail sections dominating the coupling to the (much longer) shielded section as is explained in [1,2]. SHIELD predicts these results rather well.

The comparison of the voltage transfer ratio to the right end of the second shielded wire, V_{s2}, and the predictions of SHIELD,

$$\frac{V_{\hat{w}2}(\mathcal{L})}{V_{w2}(\mathcal{L})}$$

are shown in Fig. 5-7. Here the left pigtail (3cm) is grounded but the right pigtail (zero length) is open. The predictions of SHIELD are again quite accurate. The comparison of the voltage transfer ratio to the right end of the third shielded wire, V_{s3}, and the predictions of SHIELD,

$$\frac{V_{\hat{w}3}(\mathcal{L})}{V_{w2}(\mathcal{L})}$$

are shown in Fig. 5-8 and are quite good. For this shield, the left pigtail (8cm) is ungrounded (open) and the right pigtail (8cm) is grounded (short). Note that even though the left pigtail wire is ungrounded, the program assumes the pigtail wire is present.

Note that for the unshielded wire in Fig. 5-5(a), there is a slight change in the response from a 20dB/decade (linear with frequency) response between 3 kHz and 10 kHz. Prior to this experiment the author has observed the coupling to similar unshielded wires to decrease uniformly at 20 dB/decade at the lower frequencies where the line is electrically very short. This observed behavior is, as yet, unexplainable in simple terms but SHIELD predicts this result very accurately.

This experiment tends to confirm that the SHIELD program (1) is working as intended and has no major programming errors, and (2) provides realistic predictions of crosstalk for shielded cables. The user is cautioned, however, that if the cross-sectional dimensions (wire spacing and height above ground) are not (1) known and/or (2) controlled such as occur in many types of wiring harnesses (which we refer to as random bundles) then the SHIELD program cannot be expected to provide adequate predictions [28]. However, in controlled characteristic cables such as the flatpack type, accurate predictions are achievable. Controlled characteristic flatpack type cables are presently being marketed which contain shielded cables, twisted pairs, etc. For these types of cables, the SHIELD program can be expected to provide accurate predictions.

VI. Summary

This report contains the description and verification of a digital computer program, SHIELD, to be used in the prediction of crosstalk in transmission lines consisting of U unshielded wires and/or S shielded cables. The line may be above a ground plane (TYPE 1) or within an overall, circular, cylindrical shield (TYPE 2). Each shielded cable consists of a circular, cylindrical shield which may be solid or braided and a wire (the shielded wire) located concentrically on the axis of the shield. All wires may be stranded and all conductors are treated as imperfect conductors; that is, their per-unit-length impedances are nonzero. Through-braid coupling for braided shields as well as diffusion for both types are included in the model. The shielded cables may have exposed sections at either end (pigtail sections) in which the shielded wire is not covered by the shield. Over these pigtail sections, a pigtail wire, parallel to the shielded wire, connects the shield to the reference conductor at that end via either a short circuit or an open circuit. These pigtail sections are included in the representation to simulate the common practice of terminating a shielded cable in a connector via these pigtail wires.

The multiconductor transmission line equations are solved for sinusoidal, steady-state excitation of the line. The terminal networks at the two ends of the line are modeled by a generalized Norton equivalent representation in which a current source and an admittance are connected between the reference conductor and the ends of the U unshielded wires and S shielded wires. An admittance is connected between the ends of each pair of these U+S wires. Any of these admittances may be absent, i.e., set equal to zero.

The program is rather expensive to run. For example when implemented on an IBM 370/165 digital computer using the WATFIV compiler, the program required 3.82 sec. compilation time and 84.35 sec. execution time to compute the response at 11 frequencies for the example in Section V consisting of 2 unshielded wires and 3 braided-shield cables. This represents an approximate per-frequency computation time of 8 sec. The required storage for this problem was 115192 bytes for the object deck and 32400 bytes for the arrays.

One reason for this rather lengthy run time is a result of the decision to include the capability for modeling pigtails. The program divides the overall line into cross-sectionally uniform sections. Then the chain parameter matrices for each of these uniform sections of line are determined and the overall chain parameter matrix of the line is determined as the product (in the appropriate order) of these chain parameter matrices of the individual, uniform sections. For a line consisting of U unshielded wires and S shielded cables, each chain parameter matrix is 2(U+2S) x 2(U+2S). For the example in section V consisting of 2 unshielded wires and 3 shielded cables, each chain parameter matrix was 16 x 16. Thus for a line consisting of N sections we must, at the least, multiply N such matrices together. Once the overall chain parameter matrix of the entire line is determined in this fashion we must incorporate the terminal conditions which requires several matrix multiplications and the solution of 2(U+S) simultaneous, complex equations. This process must be repeated for each frequency.

Not only must these chain parameter matrices for each section be multiplied together but they must be computed. In determining these chain parameter matrices of each section we must compute the eigenvalues and eigenvectors of a (U+2S) complex matrix. This is a result of the need to consider all conductors as being imperfect. If we had assumed all conductors as being perfect conductors, the eigenvectors and eigenvalues would not need to be computed. But if the finite conductivity of the shields are not considered, i.e., the shields are considered as perfect conductors, no coupling would occur to the interior shielded wires for solid shields - clearly an unrealistic result. For braided shields, only through-braid coupling would occur but this is almost insignificant for many typical cables. In other situations one can assume perfect conductors. For shielded cables, one cannot if one wishes to obtain predictions approaching any degree of realism. Once the decision to include shield conductivity is made we may as well include the finite conductivity of all other conductors - very little additional processing is required.

Consequently, even though the program consumes quite a bit of computation time the processing time probably cannot be reduced substantially and still have the program handle all the intended functions and structures that it now handles.

The program (the single precision version) should be easily implementable on other machines since it is written in standard Fortran IV language. For lines with known and controlled, uniform cross sections, the program provides accurate predictions. For nonuniform or random type cable bundles such as many typical wire harnesses where the relative wire positions are unknown and uncontrolled along the cable length, one cannot necessarily expect the program to provide accurate predictions.

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APPENDIX A

SHIELD Program Listing

```
C***********************************************************************
C
C                   PROGRAM SHIELD
C                   (FORTRAN IV, DOUBLE PRECISION)
C                   WRITTEN BY
C                        CLAYTON R. PAUL
C                        DEPARTMENT OF ELECTRICAL ENGINEERING
C                        UNIVERSITY OF KENTUCKY
C                        LEXINGTON, KENTUCKY 40506
C
C     A DIGITAL COMPUTER PROGRAM TO COMPUTE THE TERMINAL VOLTAGES OF
C     A MULTICONDUCTOR TRANSMISSION LINE WHICH MAY CONSIST OF
C     UNSHIELDED WIRES AND SHIELDED WIRES. THE SHIELDED WIRES
C     MAY HAVE PIGTAIL SECTIONS AND THE PIGTAIL SECTION LENGTHS
C     NEED NOT BE THE SAME.
C
C     THE DISTRIBUTED PARAMETER, MULTICONDUCTOR TRANSMISSION LINE
C     EQUATIONS ARE SOLVED FOR STEADY-STATE, SINUSOIDAL EXCITATION
C     OF THE LINE.
C
C     THE LINE CONSISTS OF NU UNSHIELDED WIRES AND NS SHIELDED WIRES.
C     THE WIRES MAY BE ABOVE A GROUND PLANE OR WITHIN AN OVERALL,
C     CIRCULAR, CYLINDRICAL SHIELD. THE IMPEDANCES OF ALL CONDUCTORS
C     ARE INCORPORATED INTO THE MODEL. THE SHIELDED WIRES MAY HAVE
C     SOLID OR BRAIDED SHIELDS. THROUGH BRAID COUPLING FOR BRAIDED
C     SHIELDS IS INCORPORATED INTO THE MODEL.
C
C     FUNCTION SUBPROGRAMS USED (AND SUPPLIED):
C        LS1,LM1,LS2,LM2,STB,LTB,ZWW,ZDB,ZSB,ZDS,ZSS
C
C     SUBROUTINES USED (AND SUPPLIED):
C           MULTC,SCAP,INDUCT,PHI,ADMADD,IMPADD
C
C     SUBROUTINES FROM THE IMSL PACKAGE USED:
C         LEQT1C,EIGCC
C
C***********************************************************************
      IMPLICIT REAL*8 (A-H,O-Z)
      REAL*8 L,MU,MUO2PI,MUO4PI,LMAXR,LMINR,LMAXL,LMINL,LS1,LM1,LS2,
     1LM2,LTRAN,LTB,LTR,LTL,LSHLD,IOR,IOI,ILR,ILI
      COMPLEX*16 ZG,JOMEGA,ONEC,ZEROC,SUMC,SUMC1,SUMC2,XJ,ZWW,
     1ZSS,ZDS,ZSB,ZDB,ZSELF,ZDIF,VWL,VWR,VSWL,VSWR
C***************************************************************C
C                                                               C
C                                                               C
C     THE FOLLOWING MATRICES AND VECTORS SHOULD HAVE THE        C
C     INDICATED DIMENSIONS WHERE                                C
C                    NU=NUMBER OF UNSHIELDED WIRES              C
C                    NS=NUMBER OF SHIELDED WIRES                C
C                    NUPS=NU+NS                                 C
C                    NT=NU+NS+NS=TOTAL NUMBER OF CONDUCTORS     C
C                    TNT=2*NT                                   C
C                    TNUPS=2*(NU+NS)                            C
C                                                               C
C                                                               C
C***************************************************************C
      INTEGER TNT,TNUPS
C***************************************************************C
C                                                               C
C     IND(NT,NT),S(NT,NT),WK(2*NT(NT+1))                        C
C                                                               C
```

```
C**********************************************************************C
      REAL*8 IND( 8, 8),SS( 8, 8),WK( 144)
C**********************************************************************C
C                                                                      C
C                                                                      C
C     Z(NT,NT),PHIR(TNT,TNT),WA(NT),YZ(NT,NT),T(NT,NT),GAM(NT),       C
C     A(NT,NT),TI(NT,NT),Y(NT,NT),YINV(NT,NT),B(NT,NT),               C
C     PHIT(TNT,TNT),C(NT,NT),D(NT,NT),EP(NT),                         C
C     EN(NT),PHIL(TNT,TNT),TPHI(TNT,TNT),IO(NUPS),IL(NUPS),           C
C     YO(NUPS,NUPS),YL(NUPS,NUPS)                                     C
C                                                                      C
C                                                                      C
C**********************************************************************C
      COMPLEX*16 Z( 8, 8),PHIR(16,16),WA( 8),YZ( 8, 8),
     1T( 8, 8),GAM( 8),A( 8, 8),TI( 8, 8),Y( 8, 8),YINV( 8, 8),
     2B( 8, 8),PHIT(16,16),C( 8, 8),D( 8, 8),EP( 8),
     3EN( 8),PHIL(16,16),TPHI(16,16),IO( 5),IL( 5),
     4YO( 5, 5),YL( 5, 5)
C**********************************************************************C
C                                                                      C
C                                                                      C
C     THE FOLLOWING ARE OF DIMENSION    NU                            C
C                                                                      C
C     NOTE: IF NU=0, SET ALL DIMENSIONS=1                             C
C                                                                      C
C                                                                      C
C**********************************************************************C
      INTEGER W(2),NWST(2)
      REAL*8 YW(2),ZW(2),RW(2),RWST(2),SIGWST(2)
      COMPLEX*16 ZWWV( 2)
C**********************************************************************C
C                                                                      C
C                                                                      C
C     THE FOLLOWING ARE OF DIMENSION    NS                            C
C                                                                      C
C     NOTE: IF NS=0, SET ALL DIMENSIONS=1                             C
C                                                                      C
C                                                                      C
C**********************************************************************C
      INTEGER S( 3),STYPE( 3),NWH( 3),BELT( 3),WPB( 3),NPI( 3),
     1NPR( 3),IGNDL( 3),IGNDR( 3),KEY( 3)
      REAL*8 YS( 3),ZS( 3),RS( 3),ERS( 3),RWH( 3),RWHST( 3),SIGWHS( 3),
     1TS( 3),SIGS( 3),RB( 3),SIGB( 3),THB( 3),LPL( 3),RPL( 3),THPL( 3),
     2RPWL( 3),SIGPWL( 3),RPWSTL( 3),LPR( 3),RPR( 3),THPR( 3),RPWR( 3),
     3RPWSTR( 3),SIGPWR( 3),LPT( 3),LTV( 3),STV( 3),
     4YPL( 3),ZPL( 3),YPR( 3),ZPR( 3)
      COMPLEX*16 ZSV( 3),ZDV( 3),ZWPLV( 3),ZWPRV( 3),ZWWHV( 3)
C
C
C     END DIMENSION STATEMENTS
C
C
      COMMON /RCON/ ZERO,ONE,TWO,THREE,FOUR,MU,MUO2PI,MUO4PI,
     1PI,RADEG,ERTE,SIGCOP,R,F,V2
      COMMON /CCON/ ZEROC,ONEC,XJ,JOMEGA
      ZERO=0.D0
      ONE=1.D0
      TWO=2.D0
      THREE=3.D0
      FOUR=4.D0
      CMTM=2.54D-5
```

```
      MUO2PI=2.D-7
      MUO4PI=1.D-7
      ONE80=180.D0
      V=2.997925D8
      SIGCOP=5.8D7
      ONEC=DCMPLX(ONE,ZERO)
      ZEROC=DCMPLX(ZERO,ZERO)
      XJ=DCMPLX(ZERO,ONE)
      PI=FOUR*DATAN(ONE)
      RADEG=ONE80/PI
      MU=MUO2PI*TWO*PI
      V2=V*V
      ERTE=ONE/(MU*V2)
C
C
C     READ INPUT DATA
C
C
      READ(5,1) NTYPE,L,NU,NS
    1 FORMAT(I1/E10.3/I2/I2)
      WRITE(6,2)
    2 FORMAT('1')
      IF(NTYPE.EQ.1) GO TO 3
      IF(NTYPE.EQ.2) GO TO 3
      GO TO 220
    3 CONTINUE
      IF(NU.EQ.0.AND.NS.EQ.0) GO TO 220
      NT=NU+NS+NS
      NUPS=NU+NS
      TNUPS=NUPS+NUPS
      TNT=NT+NT
      NNU=NU
      IF(NU.EQ.0) NNU=1
      NNS=NS
      IF(NS.EQ.0) NNS=1
      WRITE(6,4) NU,NS,L
    4 FORMAT(50X,'PROGRAM SHIELD'/////47X,I2,
     1' UNSHIELDED WIRES',//48X,I2,
     2' SHIELDED WIRES'//
     342X,'LINE LENGTH (METERS)= ',1PE11.3///)
      IF(NTYPE.EQ.1) GO TO 7
      READ(5,5) R
    5 FORMAT(10X,E10.3)
      WRITE(6,6) R
    6 FORMAT(10X,'REFERENCE CONDUCTOR IS AN OVERALL,CIRCULAR,CYLINDRICAL
     1 SHIELD WITH INTERIOR RADIUS= ',1PE10.3,' (METERS)'///)
      GO TO 9
    7 CONTINUE
      WRITE(6,8)
    8 FORMAT(40X,'REFERENCE CONDUCTOR IS A GROUND PLANE'///)
    9 CONTINUE
      IF(NU.EQ.0) GO TO 18
      WRITE(6,10)
   10 FORMAT(/////45X,'DATA FOR THE UNSHIELDED WIRES'////)
      WRITE(6,11)
   11 FORMAT(1X,'YW= WIRE HEIGHT ABOVE GROUND (METERS) OR RADIAL DISTANC
     1E FROM CENTER OF SHIELD (METERS)'/
     21X,'ZW= HORIZONTAL COORDINATE (METERS) OR ANGULAR POSITION (DEGREE
     3S)'/1X,'RW= WIRE RADIUS (MILS)'/
     41X,'NWST= NUMBER OF WIRE STRANDS'/
     51X,'RWST= RADIUS OF WIRE STRANDS (MILS)'/
```

```
   61X,'SIGWST= CONDUCTIVITY OF WIRE STRANDS (RELATIVE TO COPPER)'///
   7)
    WRITE(6,12)
 12 FORMAT(1X,'WIRE',6X,'YW',16X,'ZW',16X,'RW',12X,'NWST',8X,'RWST',
   116X,'SIGWST'/)
    DO 17 I=1,NU
    READ(5,13) W(I),YW(I),ZW(I)
 13 FORMAT(I2,8X,E10.3,10X,E10.3)
    READ(5,14) RW(I),NWST(I),RWST(I),SIGWST(I)
 14 FORMAT(10X,E10.3,13X,I2,15X,E10.3,10X,E10.3)
    WRITE(6,15) W(I),YW(I),ZW(I),RW(I),NWST(I),RWST(I),SIGWST(I)
 15 FORMAT(2X,I2,3X,1PE10.3,8X,1PE10.3,8X,1PE10.3,9X,I2,
   15X,1PE10.3,11X,1PE10.3)
    RW(I)=RW(I)*CMTM
    RWST(I)=RWST(I)*CMTM
    IF (NTYPE.EQ.1) GO TO 16
    ZW(I)=ZW(I)/RADEG
 16 CONTINUE
 17 CONTINUE
 18 CONTINUE
    IF(NS.EQ.0) GO TO 58
    WRITE(6,19)
 19 FORMAT(/////45X,'DATA FOR THE SHIELDED WIRES'////)
    WRITE(6,20)
 20 FORMAT(1X,'YS= SHIELD HEIGHT ABOVE GROUND (METERS) OR RADIAL DISTA
   1NCE FROM CENTER OF SHIELD (METERS)'/
   21X,'ZS= HORIZONTAL COORDINATE (METERS) OR ANGULAR POSITION (DEGREE
   3S)'/1X,'RS= INTERIOR SHIELD RADIUS (METERS)'/
   41X,'ERS= RELATIVE PERMITTIVITY OF INTERIOR DIELECTRIC'/
   51X,'RW= SHIELDED WIRE RADIUS (MILS)'/
   61X,'NWST= NUMBER OF SHIELDED WIRE STRANDS'/
   71X,'RWST= RADIUS OF SHIELDED WIRE STRANDS (MILS)'/
   81X,'SIGWST= CONDUCTIVITY OF SHIELDED WIRE STRANDS (RELATIVE TO COP
   9PER)'///)
    WRITE(6,21)
 21 FORMAT(2X,'SHIELD',8X,'YS',13X,'ZS',13X,'RS',13X,'ERS',12X,'RW',
   110X,'NWST',9X,'RWST',11X,'SIGWST',//)
    NTHER=0
    NSTYP=0
    DO 32 I=1,NS
    READ(5,22) S(I),STYPE(I),YS(I),ZS(I)
 22 FORMAT(I2,7X,I1,10X,E10.3,10X,E10.3)
    IF(STYPE(I).EQ.1) GO TO 23
    IF(STYPE(I).EQ.2) GO TO 23
    NSTYP=1
 23 CONTINUE
    READ(5,24) RS(I),ERS(I),RWH(I),NWH(I),RWHST(I),SIGWHS(I)
 24 FORMAT(10X,3(E10.3),10X,4X,I2,4X,2(E10.3))
    ITYPE=STYPE(I)
    GO TO (25,27), ITYPE
 25 CONTINUE
    READ(5,26) TS(I),SIGS(I)
 26 FORMAT(10X,2(E10.3))
    GO TO 29
 27 CONTINUE
    READ(5,28) RB(I),SIGB(I),THB(I),BELT(I),WPB(I)
 28 FORMAT(10X,3(E10.3),3X,I2,8X,I2)
    IF(THB(I).LT.ZERO.OR.THB(I).GT.45.D0) NTHER=1
 29 CONTINUE
    READ(5,30) LPL(I),RPL(I),THPL(I),RPWI(I),NPL(I),RPWSTL(I),
   1SIGPWL(I)
```

```
30 FORMAT(10X,3(E10.3)/10X,E10.3,3X,I2,5X,2(E10.3))
   READ(5,31) LPR(I),RPR(I),THPR(I),RPWR(I),NPR(I),RPWSTR(I),
  1SIGPWR(I)
31 FORMAT(10X,3(E10.3)/10X,E10.3,3X,I2,5X,2(E10.3))
32 CONTINUE
   IF(NTHER.EQ.1) GO TO 220
   IF(NSTYP.EQ.1) GO TO 220
   DO 35 I=1,NS
   WRITE(6,33) S(I),YS(I),ZS(I),RS(I),EBS(I),RWH(I),NWH(I),         RW
  1HST(I),SIGWHS(I)
33 FORMAT(3X,I2,7X,1PE10.3,5X,1PE10.3,5X,1PE10.3,5X,1PE10.3,
  15X,1PE10.3,7X,I2,7X,1PE10.3,5X,1PE10.3)
   RWH(I)=RWH(I)*CMTM
   RWHST(I)=RWHST(I)*CMTM
   IF (NTYPE.EQ.1) GO TO 34
   ZS(I)=ZS(I)/RADEG
34 CONTINUE
35 CONTINUE
   WRITE(6,36)
36 FORMAT(/////35X,'SHIELD CHARACTERISTICS'//)
   WRITE(6,37)
37 FORMAT(1X,'TS= SOLID SHIELD THICKNESS (MILS)'/
  11X,'SIGS= SOLID SHIELD CONDUCTIVITY (RELATIVE TO COPPER)'/
  21X,'RB= RADIUS OF BRAID WIRES (MILS)'/
  31X,'SIGB= BRAID WIRE CONDUCTIVITY (RELATIVE TO COPPER)'/
  41X,'THB= BRAID WEAVE ANGLE (DEGREES)'/
  51X,'BELTS= NUMBER OF BELTS IN BRAID'/
  61X,'WPB= NUMBER OF WIRES PER BELT'///)
   WRITE(6,38)
38 FORMAT(2X,'SHIELD',4X,'TYPE',8X,'TS',13X,'SIGS',14X,'RB',16X,
  1'SIGB',11X,'THB',10X,'BELTS',10X,'WPB'//)
   DO 43 I=1,NS
   IF(STYPE(I).EQ.2) GO TO 40
   WRITE(6,39) S(I),TS(I),SIGS(I)
39 FORMAT(3X,I2,6X,'SOLID',4X,1PE10.3,5X,1PE10.3)
   TS(I)=TS(I)*CMTM
   RS(I)=RS(I)+TS(I)
   GO TO 42
40 CONTINUE
   WRITE(6,41) S(I),RB(I),SIGB(I),THB(I),BELT(I),WPB(I)
41 FORMAT(3X,I2,5X,'BRAIDED',35X,1PE10.3,8X,1PE10.3,5X,1PE10.3,9X,
  1I2,12X,I2)
   RB(I)=RB(I)*CMTM
   TS(I)=TWO*RB(I)
   RS(I)=RS(I)+TS(I)
   THB(I)=THB(I)/RADEG
42 CONTINUE
43 CONTINUE
   WRITE(6,44)
44 FORMAT(////,39X,'DATA FOR THE PIGTAILS'//)
   WRITE(6,45)
45 FORMAT(42X,'LEFT PIGTAILS'//)
   WRITE(6,46)
46 FORMAT(1X,'LPL= LENGTH OF LEFT PIGTAIL (METERS)'/
  11X,'RPL= RADIAL SEPARATION OF PIGTAIL WIRE FROM SHIELDED WIRE (MET
  2ERS)'/
  31X,'THPL= ANGULAR POSITION OF PIGTAIL WIRE (DEGREES)'/
  41X,'RPWL= RADIUS OF PIGTAIL WIRE (MILS)'/
  51X,'NPL= NUMBER OF STRANDS IN PIGTAIL WIRE'/
  61X,'RPWSTL= RADIUS OF PIGTAIL WIRE STRANDS (MILS)'/
  71X,'SIGPWL= CONDUCTIVITY OF PIGTAIL WIRE STRANDS (RELATIVE TO COPP
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     8ER)'//)
      WRITE(6,47)
   47 FORMAT(1X,'SHIELD',9X,'LPL',14X,'RPL',12X,'THPL',10X,'RPWL',9X,
     1'NPL',9X,'RPWSTL',12X,'SIGPWL'//)
      DO 49 I=1,NS
      WRITE(6,48) S(I),LPL(I),RPL(I),THPL(I),RPWL(I),NPL(I),         RP
     1WSTL(I),SIGPWL(I)
   48 FORMAT(3X,I2,7X,1PE10.3,7X,1PE10.3,5X,1PE10.3,4X,1PE10.3,7X,
     1I2,7X,1PE10.3,8X,1PE10.3)
      RPWL(I)=RPWL(I)*CMTM
      RPWSTL(I)=RPWSTL(I)*CMTM
      THPL(I)=THPL(I)/RADEG
   49 CONTINUE
      WRITE(6,50)
   50 FORMAT(////,42X,'RIGHT PIGTAILS'//)
      WRITE(6,51)
   51 FORMAT(1X,'LPR= LENGTH OF RIGHT PIGTAIL (METERS)'/
     11X,'RPR= RADIAL SEPARATION OF PIGTAIL WIRE FROM SHIELDED WIRE (MET
     2ERS)'/
     31X,'THPR= ANGULAR POSITION OF PIGTAIL WIRE (DEGREES)'/
     41X,'RPWR= RADIUS OF PIGTAIL WIRE (MILS)'/
     51X,'NPR= NUMBER OF STRANDS IN PIGTAIL WIRE'/
     61X,'RPWSTR= RADIUS OF PIGTAIL WIRE STRANDS (MILS)'/
     71X,'SIGPWR= CONDUCTIVITY OF PIGTAIL WIRE STRANDS RELATIVE TO COPPE
     8R)'//)
      WRITE(6,52)
   52 FORMAT(1X,'SHIELD',9X,'LPR',14X,'RPR',12X,'THPR',10X,
     1'RPWR',9X,'NPR',9X,'RPWSTR',12X,'SIGPWR'//)
      DO 54 I=1,NS
      WRITE(6,53) S(I),LPR(I),RPR(I),THPR(I),RPWR(I),NPR(I),         RP
     1WSTR(I),SIGPWR(I)
   53 FORMAT(3X,I2,7X,1PE10.3,7X,1PE10.3,5X,1PE10.3,4X,1PE10.3,
     17X,I2,7X,1PE10.3,8X,1PE10.3)
      RPWR(I)=RPWR(I)*CMTM
      RPWSTR(I)=RPWSTR(I)*CMTM
      THPR(I)=THPR(I)/RADEG
   54 CONTINUE
      DO 57 I=1,NS
      IF(NTYPE.EQ.2) GO TO 55
      YPL(I)=YS(I)+RPL(I)*DSIN(THPL(I))
      ZPL(I)=ZS(I)+RPL(I)*DCOS(THPL(I))
      YPR(I)=YS(I)+RPR(I)*DSIN(THPR(I))
      ZPR(I)=ZS(I)+RPR(I)*DCOS(THPR(I))
      GO TO 56
   55 CONTINUE
      YPL(I)=DSQRT(YS(I)**2+RPL(I)**2-TWO*YS(I)*RPL(I)*DCOS(THPL(I)))
      ZPL(I)=ZS(I)+DATAN2((RPL(I)*DSIN(THPL(I))),(YS(I)+
     1RPL(I)*DCOS(THPL(I))))
      YPR(I)=DSQRT(YS(I)**2+RPR(I)**2-TWO*YS(I)*RPR(I)*DCOS(THPR(I)))
      ZPR(I)=ZS(I)+DATAN2((RPR(I)*DSIN(THPR(I))),(YS(I)+
     1RPR(I)*DCOS(THPR(I))))
   56 CONTINUE
   57 CONTINUE
   58 CONTINUE
      WRITE(6,59)
   59 FORMAT(////,33X,'TERMINAL SOURCE AND IMPEDANCE DATA'////)
      WRITE(6,60)
   60 FORMAT(1X,'IOR= REAL PART OF CURRENT SOURCE BETWEEN WIRE AND REFER
     1ENCE CONDUCTOR AT X=0'/
     21X,'IOI= IMAG PART OF CURRENT SOURCE BETWEEN WIRE AND REFERENCE CO
     3NDUCTOR AT X=0'/
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     41X,'YOR= REAL PART OF ADMITTANCE BETWEEN WIRE AND REFERENCE CONDUC
     5TOR AT X=0'/
     61X,'YOI= IMAG PART OF ADMITTANCE BETWEEN WIRE AND REFERENCE CONDUC
     7TOR AT X=0'/
     81X,'ILR= REAL PART OF CURRENT SOURCE BETWEEN WIRE AND REFERENCE CO
     9NDUCTOR AT X=L'/
     A1X,'ILI= IMAG PART OF CURRENT SOURCE BETWEEN WIRE AND REFERENCE CO
     BNDUCTOR AT X=L'/
     C1X,'YLR= REAL PART OF ADMITTANCE BETWEEN WIRE AND REFERENCE CONDUC
     DTOR AT X=L'/
     E1X,'YLI= IMAG PART OF ADMITTANCE BETWEEN WIRE AND REFERENCE CONDUC
     FTOR AT X=L'///)
      WRITE(6,61)
   61 FORMAT(1X,'WIRE',8X,'IOR',12X,'IOI',12X,'YOR',12X,'YOI',12X,
     1'ILR',12X,'ILI',12X,'YLR',12X,'YLI'//)
      IF(NU.EQ.0) GO TO 65
      DO 64 I=1,NU
      READ(5,62) IOR,IOI,YOR,YOI,ILR,ILI,YLR,YLI
   62 FORMAT(8(E10.3))
      WRITE(6,63) I,IOR,IOI,YOR,YOI,ILR,ILI,YLR,YLI
   63 FORMAT(2X,I2,5X,1PE10.3,5X,1PE10.3,5X,1PE10.3,5X,1PE10.3,5X,
     11PE10.3,5X,1PE10.3,5X,1PE10.3,5X, 1PE10.3)
      IO(I)=IOR+XJ*IOI
      IL(I)=ILR+XJ*ILI
      YO(I,I)=YOR+XJ*YOI
   64 YL(I,I)=YLR+XJ*YLI
   65 CONTINUE
      IF(NS.EQ.0) GO TO 73
      NISR=0
      NVSR=0
      NISL=0
      NVSL=0
      WRITE(6,66)
   66 FORMAT(//,1X,'SHIELDED WIRE',3X,'IOR',12X,'IOI',12X,'YOR',12X
     1,'YOI',12X,'ILR',12X,'ILI',12X,'YLR',12X,'YLI'//)
      NGNDR=0
      NGNDL=0
      DO 72 I=1,NS
      READ(5,67) IOR,IOI,YOR,YOI,ILR,ILI,YLR,YLI
   67 FORMAT(8(E10.3))
      WRITE(6,68) I,IOR,IOI,YOR,YOI,ILR,ILI,YLR,YLI
   68 FORMAT(3X,I2,8X,1PE10.3,5X,1PE10.3,5X,1PE10.3,5X,1PE10.3,5X,
     11PE10.3,5X,1PE10.3,5X,1PE10.3,5X, 1PE10.3)
      IO(I+NU)=IOR+XJ*IOI
      IL(I+NU)=ILR+XJ*ILI
      YO(I+NU,I+NU)=YOR+XJ*YOI
      YL(I+NU,I+NU)=YLR+XJ*YLI
      READ(5,69) IGNDL(I),IGNDR(I)
   69 FORMAT(9X,I1,29X,I1)
      IF(IGNDL(I).EQ.1) GO TO 70
      IF(IGNDL(I).EQ.2) GO TO 70
      NGNDL=1
   70 CONTINUE
      IF(IGNDR(I).EQ.1) GO TO 71
      IF(IGNDR(I).EQ.2) GO TO 71
      NGNDR=1
   71 CONTINUE
      IF(IGNDR(I).EQ.1) NISR=NISR+1
      IF(IGNDR(I).EQ.2) NVSR=NVSR+1
      IF(IGNDL(I).EQ.1) NISL=NISL+1
      IF(IGNDL(I).EQ.2) NVSL=NVSL+1
```

```
72 CONTINUE
   IF(NGNDL.EQ.1.OR.NGNDR.EQ.1) GO TO 220
73 CONTINUE
   K1=NUPS-1
   DO 75 I=1,K1
   IP1=I+1
   DO 75 J=IP1,NUPS
   READ(5,74) YOR,YOI,YLR,YLI
74 FORMAT(20X,2(E10.3),20X,2(E10.3))
   YO(I,J)=YOR+XJ*YOI
   YL(I,J)=YLR+XJ*YLI
   YO(J,I)=YO(I,J)
75 YL(J,I)=YL(I,J)
   WRITE(6,76)
76 FORMAT(//,10X,'IMPEDANCES BETWEEN WIRES'//)
   IF(NU.EQ.0) GO TO 80
   WRITE(6,77)
77 FORMAT(1X,'WIRE',2X,'WIRE',18X,'YOR',12X,'YOI',12X,'YLR',12X,
  1'YLI'//)
   MKN=NU-1
   DO 79 I=1,MKN
   IP1=I+1
   DO 79 J=IP1,NU
   WRITE(6,78) I,J,YO(I,J),YL(I,J)
78 FORMAT(2X,I2,4X,I2,15X,1PE10.3,5X,1PE10.3,5X,1PE10.3,5X,1PE10.3)
79 CONTINUE
80 CONTINUE
   IF(NU.EQ.0.OR.NS.EQ.0) GO TO 84
   WRITE(6,81)
81 FORMAT(///,1X,'WIRE',2X,'SHIELDED WIRE',12X,'YOR',12X,'YOI',12X,
  1'YLR',12X,'YLR'//)
   DO 83 I=1,NU
   DO 83 J=1,NS
   WRITE(6,82) I,J,YO(I,J+NU),YL(I,J+NU)
82 FORMAT(2X,I2,7X,I2,15X,1PE10.3,5X,1PE10.3,5X,1PE10.3,5X,
  11PE10.3)
83 CONTINUE
84 CONTINUE
   IF(NS.EQ.0) GO TO 100
   WRITE(6,85)
85 FORMAT(///,1X,'SHIELDED WIRE',2X,'SHIELDED WIRE',7X,
  1'YOR',19X,'YOI',19X,'YLR',19X,'YLI'//)
   MKS=NS-1
   DO 87 I=1,MKS
   IP1=I+1
   DO 87 J=IP1,NS
   WRITE(6,86) I,J,YO(I+NU,J+NU),YL(I+NU,J+NU)
86 FORMAT(5X,I2,13X,I2,10X,1PE10.3,12X,1PE10.3,12X,1PE10.3,
  112X,1PE10.3)
87 CONTINUE
   WRITE(6,88)
88 FORMAT(////,20X,'SHIELD TERMINATION DATA'//)
   WRITE(6,89)
89 FORMAT(1X,'SHIELD',5X,'TERMINATION AT X=0',
  110X,'TERMINATION AT X=L'//)
   DO 99 I=1,NS
   IF(IGNDL(I).EQ.1.AND.IGNDR(I).EQ.1) GO TO 90
   IF(IGNDL(I).EQ.1.AND.IGNDR(I).EQ.2) GO TO 92
   IF(IGNDL(I).EQ.2.AND.IGNDR(I).EQ.1) GO TO 94
   IF(IGNDL(I).EQ.2.AND.IGNDR(I).EQ.2) GO TO 96
90 CONTINUE
```

```
      WRITE(6,91) I
   91 FORMAT(3X,I2,12X,'SHORT',23X,'SHORT')
      GO TO 98
   92 CONTINUE
      WRITE(6,93) I
   93 FORMAT(3X,I2,12X,'SHORT',24X,'OPEN')
      GO TO 98
   94 CONTINUE
      WRITE(6,95) I
   95 FORMAT(3X,I2,13X,'OPEN',23X,'SHORT')
      GO TO 98
   96 CONTINUE
      WRITE(6,97) I
   97 FORMAT(3X,I2,13X,'OPEN',24X,'OPEN')
   98 CONTINUE
   99 CONTINUE
  100 CONTINUE
      DO 101 I=1,NUPS
      DO 101 J=1,NUPS
      YO(I,J)=-YO(I,J)
  101 YL(I,J)=-YL(I,J)
      DO 103 I=1,NUPS
      SUMC1=ZEROC
      SUMC2=ZEROC
      DO 102 J=1,NUPS
      SUMC1=SUMC1+YO(I,J)
  102 SUMC2=SUMC2+YL(I,J)
      YO(I,I)=-SUMC1
  103 YL(I,I)=-SUMC2
  104 CONTINUE
C
C
C     READ FREQUENCY AND COMPUTE CONDUCTOR IMPEDANCES
C
C
      READ(5,105,END=225) F
  105 FORMAT(E10.3)
      OMEGA=TWO*PI*F
      JOMEGA=XJ*OMEGA
      READ(5,106) ZGR,ZGI
  106 FORMAT(2(E10.3))
      ZG=DCMPLX(ZGR,ZGI)
      WRITE(6,107) F,ZGR,ZGI
  107 FORMAT(////,1X,'FREQUENCY(HZ)= ',1PE10.3//
     11X,'REFERENCE CONDUCTOR IMPEDANCE= ',1PE10.3,' +J ',
     21PE10.3,' OHMS PER METER')
      IF(NU.EQ.0) GO TO 109
      DO 108 I=1,NU
  108 ZWWV(I)=ZWW(RWST(I),NWST(I),SIGWST(I))
  109 CONTINUE
      IF(NS.EQ.0) GO TO 113
      DO 112 I=1,NS
      ZWWHV(I)=ZWW(RWHST(I),NWH(I),SIGWHS(I))
      ZWPLV(I)=ZWW(RPWSTL(I),NPL(I),SIGPWL(I))
      ZWPRV(I)=ZWW(RPWSTR(I),NPR(I),SIGPWR(I))
      IF(STYPE(I).EQ.2) GO TO 110
      ZSV(I)=ZSS(RS(I),TS(I),SIGS(I))
      ZDV(I)=ZDS(RS(I),TS(I),SIGS(I))
      LTV(I)=ZERO
      STV(I)=ZERO
      GO TO 111
```

```
  110 CONTINUE
      ZSV(I)=ZSB(RS(I),RB(I),SIGB(I),THB(I),
     1BELT(I),WPB(I))
      ZDV(I)=ZDB(RS(I),RB(I),SIGB(I),THB(I),
     1BELT(I),WPB(I))
      LTV(I)=LTB(RS(I),RB(I),THB(I),
     1BELT(I),WPB(I))
      STV(I)=STB(RS(I),RB(I),THB(I),
     1BELT(I),WPB(I),ERS(I))
  111 CONTINUE
  112 CONTINUE
  113 CONTINUE
      IF(NS.EQ.0) GO TO 164
C
C
C     COMPUTE CHAIN PARAMETER MATRICES FOR
C     RIGHT PIGTAIL SECTIONS
C
C
      DO 114 I=1,NS
  114 LPT(I)=LPR(I)
      IPR=0
      LMAXR=ZERO
      DO 116 I=1,TNT
      DO 115 J=1,TNT
  115 PHIR(I,J)=ZEROC
  116 PHIR(I,I)=ONEC
  117 CONTINUE
      DO 118 I=1,NS
  118 IF(LPT(I).GE.LMAXR) LMAXR=LPT(I)
      IF(IPR.EQ.0) LTR=LMAXR
      IF(LMAXR.EQ.ZERO) GO TC 132
      IPR=IPR+1
      LMINR=LMAXR
      DO 119 I=1,NS
  119 IF(LPT(I).LE.LMINR.AND.LPT(I).NE.ZERC) LMINR=LPT(I)
      DO 120 I=1,NS
      KEY(I)=1
  120 IF(LPT(I).GE.LMINR) KEY(I)=2
      CALL INDUCT(IND,NU,NS,NT,NUPS,NTYPE,RW,YW,ZW,RS,YS,ZS,
     1REWR,YPR,ZPR,RWH,KEY,NNU,NNS)
      DO 121 I=1,NT
      DO 121 J=1,NT
  121 Z(I,J)=JOMEGA*IND(I,J)+ZG
      IF(NU.EQ.0) GO TO 123
      DO 122 I=1,NU
  122 Z(I,I)=Z(I,I)+ZWWV(I)
  123 CONTINUE
      CALL  IMPADD(Z,KEY,NU,NS,NT,NUPS,ZSV,ZDV,LTV,ZWPRV,ZWWHV,NNU,NNS)
      CALL SCAP(SS,IND,NU,NS,NT,NUPS,KEY,NNU,NNS)
      CALL ADMADD(KEY,NU,NS,NT,NUPS,RS,TS,RWH,ERS,SS,STV,NNU,NNS)
      DO 125 I=1,NT
      DO 124 J=1,NT
      T(I,J)=SS(I,J)*ONEC
  124 TI(I,J)=ZEROC
  125 TI(I,I)=ONEC
      CALL LEQT1C(T,NT,NT,TI,NT,NT,0,WA,IER)
      DO 126 I=1,NT
      DO 126 J=1,NT
      Y(I,J)=JOMEGA*DREAL(TI(I,J))
  126 YINV(I,J)=SS(I,J)/JOMEGA
```

```
      CALL MULTC(TI,Y,Z,NT,NT,NT)
      CALL EIGCC(TI,NT,NT,2,GAM,T,NT,WK,IER)
      DO 128 I=1,NT
      DO 127 J=1,NT
      Z(I,J)=T(I,J)
  127 TI(I,J)=ZEROC
  128 TI(I,I)=ONEC
      CALL LEQT1C(Z,NT,NT,TI,NT,NT,0,WA,IER)
      DO 129 I=1,NT
  129 GAM(I)=CDSQRT(GAM(I))
      CALL PHI(PHIT,NT,TNT,LMINR,GAM,Y,YINV,T,TI,EP,EN)
      CALL MULTC(TPHI,PHIR,PHIT,TNT,TNT,TNT)
      DO 130 I=1,TNT
      DO 130 J=1,TNT
  130 PHIR(I,J)= TPHI(I,J)
      DO 131 I=1,NS
  131 IF(LPT(I).NE.ZERO) LPT(I)=LPT(I)-LMINR
      LMAXR=ZERO
      GO TO 117
  132 CONTINUE
      WRITE(6,133) IPR
  133 FORMAT(//10X,'THE NUMBER OF RIGHT PIGTAIL SECTIONS =
     1,I2//)
C
C
C     COMPUTE CHAIN PARAMETER MATRICES FOR
C     LEFT PIGTAIL SECTIONS
C
C
      DO 134 I=1,NS
  134 LPT(I)=LPL(I)
      IPL=0
      LMAXL=ZERO
      DO 136 I=1,TNT
      DO 135 J=1,TNT
  135 PHIL(I,J)=ZEROC
  136 PHIL(I,I)=ONEC
  137 CONTINUE
      DO 138 I=1,NS
  138 IF(LPT(I).GE.LMAXL) LMAXL=LPT(I)
      IF(IPL.EQ.0) LTL=LMAXL
      IF(LMAXL.EQ.ZERO) GO TO 152
      IPL=IPL+1
      LMINL=LMAXL
      DO 139 I=1,NS
  139 IF(LPT(I).LE.LMINL.AND.LPT(I).NE.ZERO) LMINL=LPT(I)
      DO 140 I=1,NS
      KEY(I)=1
  140 IF(LPT(I).GE.LMINL) KEY(I)=2
      CALL INDUCT(IND,NU,NS,NT,NUPS,NTYPE,RW,YW,ZW,RS,YS,ZS,
     1RPWL,YPL,ZPL,RWH,KEY,NNU,NNS)
      DO 141 I=1,NT
      DO 141 J=1,NT
  141 Z(I,J)=JOMEGA*IND(I,J)+ZG
      IF(NU.EQ.0) GO TO 143
      DO 142 I=1,NU
  142 Z(I,I)=Z(I,I)+ZWWV(I)
  143 CONTINUE
      CALL IMPADD(Z,KEY,NU,NS,NT,NUPS,ZSV,ZDV,LTV,ZWPLV,ZWWHV,NNU,NNS)
      CALL SCAP(SS,IND,NU,NS,NT,NUPS,KEY,NNU,NNS)
      CALL ADMADD(KEY,NU,NS,NT,NUPS,RS,YS,RWH,ERS,SS,STV,NNU,NNS)
```

```
      DO 145 I=1,NT
      DO 144 J=1,NT
      T(I,J)=SS(I,J)*ONEC
  144 TI(I,J)=ZEROC
  145 TI(I,I)=ONEC
      CALL LEQT1C(T,NT,NT,TI,NT,NT,0,WA,IER)
      DO 146 I=1,NT
      DO 146 J=1,NT
      Y(I,J)=JOMEGA*DREAL(TI(I,J))
  146 YINV(I,J)=SS(I,J)/JOMEGA
      CALL MULTC(TI,Y,Z,NT,NT,NT)
      CALL EIGCC(TI,NT,NT,2,GAM,T,NT,WK,IER)
      DO 148 I=1,NT
      DO 147 J=1,NT
      Z(I,J)=T(I,J)
  147 TI(I,J)=ZEROC
  148 TI(I,I)=ONEC
      CALL LEQT1C(Z,NT,NT,TI,NT,NT,0,WA,IER)
      DO 149 I=1,NT
  149 GAM(I)=CDSQRT(GAM(I))
      CALL PHI(PHIT,NT,TNT,LMINL,GAM,Y,YINV,T,TI,EP,EN)
      CALL MULTC(TPHI,PHIT,PHIL,TNT,TNT,TNT)
      DO 150 I=1,TNT
      DO 150 J=1,TNT
  150 PHIL(I,J)=TPHI(I,J)
      DO 151 I=1,NS
  151 IF(LPT(I).NE.ZERO) LPT(I)=LPT(I)-LMINL
      IFAXL=ZERO
      GO TO 137
  152 CONTINUE
      WRITE(6,153) IPL
  153 FORMAT(//10X,'THE NUMBER OF LEFT PIGTAIL SECTIONS =  '
     1,I2//)
C
C
C     COMPUTE CHAIN PARAMETER MATRIX FOR
C     SHIELDED SECTION
C
C
      LSHLD=L-LTL-LTR
      IF(LSHLD.LE.ZERO) GO TO 222
      DO 154 I=1,NS
  154 KEY(I)=1
      CALL INDUCT(IND,NU,NS,NT,NUPS,NTYPE,RW,YW,ZW,RS,YS,ZS,
     1RPWR,YPR,ZPR,RWH,KEY,NNU,NNS)
      DO 155 I=1,NT
      DO 155 J=1,NT
  155 Z(I,J)=JOMEGA*IND(I,J)+ZG
      IF(NU.EQ.0) GO TO 157
      DO 156 I=1,NU
  156 Z(I,I)=Z(I,I)+ZWWV(I)
  157 CONTINUE
      CALL IMPADD(Z,KEY,NU,NS,NT,NUPS,ZSV,ZDV,LTV,ZWPLV,ZWWHV,NNU,NNS)
      CALL SCAP(SS,IND,NU,NS,NT,NUPS,KEY,NNU,NNS)
      CALL ADMADD(KEY,NU,NS,NT,NUPS,RS,TS,BWH,ERS,SS,STV,NNU,NNS)
      DO 159 I=1,NT
      DO 158 J=1,NT
      T(I,J)=SS(I,J)*ONEC
  158 TI(I,J)=ZEROC
  159 TI(I,I)=ONEC
      CALL LEQT1C(T,NT,NT,TI,NT,NT,0,WA,IER)
```

```
      DO 160 I=1,NT
      DO 160 J=1,NT
      Y(I,J)=JOMEGA*DREAL(TI(I,J))
  160 YINV(I,J)=SS(I,J)/JOMEGA
      CALL MULTC(TI,Y,Z,NT,NT,NT)
      CALL EIGCC(TI,NT,NT,2,GAM,T,NT,WK,IER)
      DO 162 I=1,NT
      DO 161 J=1,NT
      Z(I,J)=T(I,J)
  161 TI(I,J)=ZEROC
  162 TI(I,I)=ONEC
      CALL LEQT1C(Z,NT,NT,TI,NT,NT,0,WA,IER)
      DO 163 I=1,NT
  163 GAM(I)=CDSQRT(GAM(I))
      CALL PHI(TPHI,NT,TNT,LSHLD,GAM,Y,YINV,T,TI,EP,EN)
      CALL MULTC(PHIT,TPHI,PHII,TNT,TNT,TNT)
      CALL MULTC(TPHI,PHIR,PHIT,TNT,TNT,TNT)
      GO TO 173
C
C
C     COMPUTE CHAIN PARAMETER MATRICES FOR
C     LINE HAVING NO SHIELDED WIRES
C
C
  164 CONTINUE
      CALL INDUCT(IND,NU,NS,NT,NUPS,NTYPE,RW,YW,ZW,RS,YS,ZS,
     1REWF,YPR,ZPR,RWH,KEY,NNU,NNS)
      DO 165 I=1,NT
      DO 165 J=1,NT
  165 Z(I,J)=JOMEGA*IND(I,J)+ZG
      DO 166 I=1,NU
  166 Z(I,I)=Z(I,I)+ZWWV(I)
      CALL SCAP(SS,IND,NU,NS,NT,NUPS,KEY,NNU,NNS)
      DO 168 I=1,NT
      DO 167 J=1,NT
      T(I,J)=SS(I,J)*ONE
  167 TI(I,J)=ZEROC
  168 TI(I,I)=ONEC
      CALL LEQT1C(T,NT,NT,TI,NT,NT,0,WA,IER)
      DO 169 I=1,NT
      DO 169 J=1,NT
      Y(I,J)=JOMEGA*DREAL(TI(I,J))
  169 YINV(I,J)=SS(I,J)/JOMEGA
      CALL MULTC(TI,Y,Z,NT,NT,NT)
      CALL EIGCC(TI,NT,NT,2,GAM,T,NT,WK,IER)
      DO 171 I=1,NT
      DO 170 J=1,NT
      Z(I,J)=T(I,J)
  170 TI(I,J)=ZEROC
  171 TI(I,I)=ONEC
      CALL LEQT1C(Z,NT,NT,TI,NT,NT,0,WA,IER)
      DO 172 I=1,NT
  172 GAM(I)=CDSQRT(GAM(I))
      CALL PHI(TPHI,NT,TNT,1,GAM,Y,YINV,T,TI,EP,EN)
  173 CONTINUE
C
C
C     REARRANGE PHI MATRIX
C
C
C     REARRANGE ROWS
```

```
C
C
      IF(NU.EQ.0) GO TO 175
      DO 174 I=1,NU
      DO 174 J=1,TNT
      PHIT(I,J)=TPHI(I,J)
  174 PHIT(I+NUPS,J)=TPHI(I+NT,J)
  175 CONTINUE
      IF(NS.EQ.0) GO TO 182
      DO 176 I=1,NS
      DO 176 J=1,TNT
      PHIT(I+NU,J)=TPHI(I+NUPS,J)
  176 PHIT(I+NUPS+NU,J)=TPHI(I+NT+NUPS,J)
      K=0
      M=0
      DO 181 I=1,NS
      IF(IGNDR(I).EQ.1) GO TO 178
      K=K+1
      DO 177 J=1,TNT
      PHIT(K+TNUPS,J)=TPHI(I+NU,J)
  177 PHIT(K+TNUPS+NS+NISR,J)=TPHI(I+TNUPS,J)
      GO TO 180
  178 CONTINUE
      M=M+1
      DO 179 J=1,TNT
      PHIT(M+TNUPS+NVSR,J)=TPHI(I+TNUPS,J)
  179 PHIT(M+TNUPS+NS,J)=TPHI(I+NU,J)
  180 CONTINUE
  181 CONTINUE
  182 CONTINUE
      DO 183 I=1,TNT
      DO 183 J=1,TNT
  183 TPHI(I,J)=PHIT(I,J)
C
C
C     REARRANGE COLUMNS
C
C
      IF(NU.EQ.0) GO TO 185
      DO 184 J=1,NU
      DO 184 I=1,TNT
      PHIT(I,J)=TPHI(I,J)
  184 PHIT(I,J+NUPS)=TPHI(I,J+NT)
  185 CONTINUE
      IF(NS.EQ.0) GO TO 192
      DO 186 J=1,NS
      DO 186 I=1,TNT
      PHIT(I,J+NU)=TPHI(I,J+NUPS)
  186 PHIT(I,J+NUPS+NU)=TPHI(I,J+NT+NUPS)
      K=0
      M=0
      DO 191 J=1,NS
      IF(IGNDL(J).EQ.1) GO TO 188
      K=K+1
      DO 187 I=1,TNT
      PHIT(I,K+TNUPS)=TPHI(I,J+NU)
  187 PHIT(I,K+TNUPS+NS+NISL)=TPHI(I,J+TNUPS)
      GO TO 190
  188 CONTINUE
      M=M+1
      DO 189 I=1,TNT
```

```
      PHIT(I,M+TNUPS+NVSL)=TPHI(I,J+TNUPS)                              SHLD0855
  189 PHIT(I,M+TNUPS+NS)=TPHI(I,J+NU)                                   SHLD0856
  190 CONTINUE                                                          SHLD0857
  191 CONTINUE                                                          SHLD0858
  192 CONTINUE                                                          SHLD0859
C                                                                       SHLD0860
C                                                                       SHLD0861
C     INCORPORATE TERMINAL CONDITIONS                                   SHLD0862
C                                                                       SHLD0863
C                                                                       SHLD0864
      DO 194 I=1,NUPS                                                   SHLD0865
      DO 194 J=1,NUPS                                                   SHLD0866
      SUMC=ZEROC                                                        SHLD0867
      SUMC1=ZEROC                                                       SHLD0868
      SUMC2=ZEROC                                                       SHLD0869
      DO 193 K=1,NUPS                                                   SHLD0870
      SUMC=SUMC+PHIT(I,K+NUPS)*YO(K,J)                                  SHLD0871
      SUMC1=SUMC1+PHIT(I+NUPS,K+NUPS)*YO(K,J)                           SHLD0872
  193 SUMC2=SUMC2+YL(I,K)*PHIT(K,J+NUPS)                                SHLD0873
      B(I,J)=-SUMC+PHIT(I,J)                                            SHLD0874
      C(I,J)=SUMC1-PHIT(I+NUPS,J)                                       SHLD0875
  194 D(I,J)=-SUMC2+PHIT(I+NUPS,J+NUPS)                                 SHLD0876
      IF(NS.EQ.0) GO TO 199                                             SHLD0877
      DO 196 I=1,NUPS                                                   SHLD0878
      DO 196 J=1,NS                                                     SHLD0879
      SUMC=ZEROC                                                        SHLD0880
      DO 195 K=1,NUPS                                                   SHLD0881
  195 SUMC=SUMC+YL(I,K)*PHIT(K,J+TNUPS)                                 SHLD0882
  196 A(I,J+NUPS)=SUMC-PHIT(I+NUPS,J+TNUPS)                             SHLD0883
      DO 198 I=1,NS                                                     SHLD0884
      DO 198 J=1,NUPS                                                   SHLD0885
      SUMC=ZEROC                                                        SHLD0886
      DO 197 K=1,NUPS                                                   SHLD0887
  197 SUMC=SUMC+PHIT(I+TNUPS+NS,K+NUPS)*YO(K,J)                         SHLD0888
  198 A(I+NUPS,J)=SUMC-PHIT(I+TNUPS+NS,J)                               SHLD0889
  199 CONTINUE                                                          SHLD0890
      DO 202 I=1,NUPS                                                   SHLD0891
      SUMC=ZEROC                                                        SHLD0892
      DO 201 J=1,NUPS                                                   SHLD0893
      SUMC1=ZEROC                                                       SHLD0894
      DO 200 K=1,NUPS                                                   SHLD0895
  200 SUMC1=SUMC1+YL(I,K)*B(K,J)                                        SHLD0896
      A(I,J)=C(I,J)+SUMC1                                               SHLD0897
  201 SUMC=SUMC+D(I,J)*IO(J)                                            SHLD0898
  202 EP(I)=IL(I)+SUMC                                                  SHLD0899
      IF(NS.EQ.0) GO TO 206                                             SHLD0900
      DO 203 I=1,NS                                                     SHLD0901
      DO 203 J=1,NS                                                     SHLD0902
  203 A(I+NUPS,J+NUPS)=-PHIT(I+TNUPS+NS,J+TNUPS)                        SHLD0903
      DO 205 I=1,NS                                                     SHLD0904
      SUMC=ZEROC                                                        SHLD0905
      DO 204 J=1,NUPS                                                   SHLD0906
  204 SUMC=SUMC+PHIT(I+TNUPS+NS,J+NUPS)*IO(J)                           SHLD0907
  205 EP(I+NUPS)=SUMC                                                   SHLD0908
  206 CONTINUE                                                          SHLD0909
      CALL LEQT1C(A,NT,NT,EP,1,NT,0,WA,IER)                             SHLD0910
      DO 208 I=1,NUPS                                                   SHLD0911
      SUMC=ZEROC                                                        SHLD0912
      SUMC1=ZEROC                                                       SHLD0913
      DO 207 J=1,NUPS                                                   SHLD0914
      SUMC=SUMC+B(I,J)*EP(J)                                            SHLD0915
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  207 SUMC1=SUMC1+PHIT(I,J+NUPS)*IO(J)                                   SHLD0916
  208 EN(I)=SUMC+SUMC1                                                   SHLD0917
      IF(NS.EQ.0) GO TO 211                                              SHLD0918
      DO 210 I=1,NUPS                                                    SHLD0919
      SUMC=ZEROC                                                         SHLD0920
      DO 209 J=1,NS                                                      SHLD0921
  209 SUMC=SUMC+PHIT(I,J+TNUPS)*EP(J+NUPS)                               SHLD0922
  210 EN(I)=EN(I)+SUMC                                                   SHLD0923
  211 CONTINUE                                                           SHLD0924
      IF(NU.EQ.0) GO TO 215                                              SHLD0925
      WRITE(6,212)                                                       SHLD0926
  212 FORMAT(/////,1X,'WIRE',14X,'VOM(VOLTS)',15X,'VOA(DEGREES)',        SHLD0927
     128X,'VIM(VOLTS)',15X,'VLA(DEGREES)'//)                             SHLD0928
      DO 214 I=1,NU                                                      SHLD0929
      VWL=EP(I)                                                          SHLD0930
      VWLM=CDABS(VWL)                                                    SHLD0931
      VWLR=DREAL(VWL)                                                    SHLD0932
      VWLI=DIMAG(VWL)                                                    SHLD0933
      VWLA=DATAN2(VWLI,VWLR)*RADEG                                       SHLD0934
      VWR=EN(I)                                                          SHLD0935
      VWRM=CDABS(VWR)                                                    SHLD0936
      VWRR=DREAL(VWR)                                                    SHLD0937
      VWRI=DIMAG(VWR)                                                    SHLD0938
      VWRA=DATAN2(VWRI,VWRR)*RADEG                                       SHLD0939
      WRITE(6,213)I,VWLM,VWLA,VWRM,VWRA                                  SHLD0940
  213 FORMAT(1X,I2,2(15X,1PE10.3),15X,2(15X,1PE10.3))                    SHLD0941
  214 CONTINUE                                                           SHLD0942
  215 CONTINUE                                                           SHLD0943
      IF(NS.EQ.0) GO TO 219                                              SHLD0944
      WRITE(6,216)                                                       SHLD0945
  216 FORMAT(///,1X,'SHIELDED WIRE',5X,'VOM(VOLTS)',15X,'VOA(DEGREES)',  SHLD0946
     128X,'VIM(VOLTS)',15X,'VLA(DEGREES)'//)                             SHLD0947
      DO 218 I=1,NS                                                      SHLD0948
      VSWL=EP(I+NU)                                                      SHLD0949
      VSWLM=CDABS(VSWL)                                                  SHLD0950
      VSWLR=DREAL(VSWL)                                                  SHLD0951
      VSWLI=DIMAG(VSWL)                                                  SHLD0952
      VSWLA=DATAN2(VSWLI,VSWLR)*RADEG                                    SHLD0953
      VSWR=EN(I+NU)                                                      SHLD0954
      VSWRM=CDABS(VSWR)                                                  SHLD0955
      VSWRR=DREAL(VSWR)                                                  SHLD0956
      VSWRI=DIMAG(VSWR)                                                  SHLD0957
      VSWRA=DATAN2(VSWRI,VSWRR)*RADEG                                    SHLD0958
      WRITE(6,217)I,VSWLM,VSWLA,VSWRM,VSWRA                              SHLD0959
  217 FORMAT(1X,I2,2(15X,1PE10.3),15X,2(15X,1PE10.3))                    SHLD0960
  218 CONTINUE                                                           SHLD0961
  219 CONTINUE                                                           SHLD0962
      GO TO 104                                                          SHLD0963
  220 CONTINUE                                                           SHLD0964
      WRITE(6,221)                                                       SHLD0965
  221 FORMAT(20X,'INPUT DATA ERROR'/                                     SHLD0966
     120X,'CONSULT USERS MANUAL FOR ALLOWED RANGE OF FORMAT')            SHLD0967
      GO TO 224                                                          SHLD0968
  222 CONTINUE                                                           SHLD0969
      WRITE(6,223)                                                       SHLD0970
  223 FORMAT(10X,'THERE IS A ZERO OR NEGATIVE LENGTH SHIELD ON A SHIELDESHLD0971
     1D WIRE'/10X,'CHECK PIGTAIL LENGTHS AGAINST TOTAL LINE LENGTH')     SHLD0972
  224 CONTINUE                                                           SHLD0973
  225 STOP                                                               SHLD0974
      END                                                                SHLD0975
C                                                                        FLS10001
```

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C                                                                       FLS10002
C     FUNCTION LS1 FOR COMPUTING THE SELF INDUCTANCES OF CONDUCTORS     FLS10003
C     ABOVE GROUND                                                      FLS10004
C                                                                       FLS10005
C                                                                       FLS10006
      REAL FUNCTION LS1*8(RW,H)                                         FLS10007
      IMPLICIT REAL*8 (A-H,O-Z)                                         FLS10008
      REAL*8 MU,MUO2PI,MUO4PI                                           FLS10009
      COMMON /RCON/ ZERO,ONE,TWO,THREE,FOUR,MU,MUO2PI,MUO4PI,           FLS10010
     1PI,RADEG,ERTE,SIGCOP,R,F,V2                                       FLS10011
      LS1=MUO2PI*DLOG(TWO*H/RW)                                         FLS10012
      RETURN                                                            FLS10013
      END                                                               FLS10014
C                                                                       FLM10001
C                                                                       FLM10002
C     FUNCTION LM1 FOR COMPUTING MUTUAL INDUCTANCES OF CONDUCTORS       FLM10003
C     ABOVE GROUND                                                      FLM10004
C                                                                       FLM10005
C                                                                       FLM10006
      REAL FUNCTION LM1*8(YI,YJ,ZI,ZJ)                                  FLM10007
      IMPLICIT REAL*8 (A-H,O-Z)                                         FLM10008
      REAL*8 MU,MUO2PI,MUO4PI                                           FLM10009
      COMMON /RCON/ ZERO,ONE,TWO,THREE,FOUR,MU,MUO2PI,MUO4PI,           FLM10010
     1PI,RADEG,ERTE,SIGCOP,R,F,V2                                       FLM10011
      ZD=ZI-ZJ                                                          FLM10012
      YD=YI-YJ                                                          FLM10013
      DIJ2=ZD*ZD+YD*YD                                                  FLM10014
      LM1=MUO4PI*DLOG(ONE+FOUR*YI*YJ/DIJ2)                              FLM10015
      RETURN                                                            FLM10016
      END                                                               FLM10017
C                                                                       FLS20001
C                                                                       FLS20002
C     FUNCTION LS2 FOR COMPUTING THE SELF INDUCTANCES OF CONDUCTORS     FLS20003
C     IN AN OVERALL SHIELD                                              FLS20004
C                                                                       FLS20005
C                                                                       FLS20006
      REAL FUNCTION LS2*8(RWI,RI)                                       FLS20007
      IMPLICIT REAL*8 (A-H,O-Z)                                         FLS20008
      REAL*8 MU,MUO2PI,MUO4PI                                           FLS20009
      COMMON /RCON/ ZERO,ONE,TWO,THREE,FOUR,MU,MUO2PI,MUO4PI,           FLS20010
     1PI,RADEG,ERTE,SIGCOP,R,F,V2                                       FLS20011
      LS2=MUO2PI*DLOG((R*R-RI*RI)/(R*RWI))                              FLS20012
      RETURN                                                            FLS20013
      END                                                               FLS20014
C                                                                       FLM20001
C                                                                       FLM20002
C     FUNCTION LM2 FOR COMPUTING THE MUTUAL INDUCTANCES OF CONDUCTORS   FLM20003
C     IN AN OVERALL SHIELD                                              FLM20004
C                                                                       FLM20005
C                                                                       FLM20006
      REAL FUNCTION LM2*8(RI,RJ,THI,THJ)                                FLM20007
      IMPLICIT REAL*8 (A-H,O-Z)                                         FLM20008
      REAL*8 MU,MUO2PI,MUO4PI                                           FLM20009
      COMMON /RCON/ ZERO,ONE,TWO,THREE,FOUR,MU,MUO2PI,MUO4PI,           FLM20010
     1PI,RADEG,ERTE,SIGCOP,R,F,V2                                       FLM20011
      RI2=RI*RI                                                         FLM20012
      RJ2=RJ*RJ                                                         FLM20013
      THETA=THI-THJ                                                     FLM20014
      RS2=R*R                                                           FLM20015
      LM2=MUO4PI*DLOG((RJ2/RS2)*(RI2*RJ2+RS2*RS2-TWO*RI*RJ*RS2*         FLM20016
     1DCOS(THETA))/(RI2*RJ2+RJ2*RJ2-TWO*RI*RJ*RJ2*DCOS(THETA)))         FLM20017
```

```
      RETURN                                                            FLM20018
      END                                                               FLM20019
C                                                                       FSTB0001
C                                                                       FSTB0002
C     FUNCTION STB FOR COMPUTING THE TRANSFER ELASTANCES FOR            FSTB0003
C     BRAIDED SHIELDS                                                   FSTB0004
C                                                                       FSTB0005
C                                                                       FSTB0006
      REAL FUNCTION STB*8(RS,RB,THW,B,WPB,ERS)                          FSTB0007
      IMPLICIT REAL*8 (A-H,O-Z)                                         FSTB0008
      INTEGER B,WPB                                                     FSTB0009
      REAL*4 TABLH(5,9)                                                 FSTB0010
      REAL*8 MU,MUO2PI,MUO4PI                                           FSTB0011
      COMMON /RCON/ ZERO,ONE,TWO,THREE,FOUR,MU,MUO2PI,MUO4PI,           FSTB0012
     1PI,RADEG,ERTE,SIGCOP,R,F,V2                                       FSTB0013
      DATA TABLH/.521,1.036,1.545,2.049,2.547,.502,1.001,1.496,         FSTB0014
     11.987,2.475,.491,.987,1.463,1.944,2.423,.480,.956,1.431,          FSTB0015
     21.902,2.371,.471,.939,1.404,1.866,2.326,.463,.922,1.379,          FSTB0016
     31.834,2.285,.458,.912,1.364,1.813,2.259,.455,.906,1.355,          FSTB0017
     41.801,2.244,.454,.904,1.352,1.796,2.238/                          FSTB0018
      THW=THW*RADEG                                                     FSTB0019
      XF=FLOAT(B)*FLOAT(WPB)*TWO*RB/(FOUR*PI*RS*DCOS(THW/RADEG))        FSTB0020
      OPC=TWO*XF-XF*XF                                                  FSTB0021
      FAC=((ONE-OPC)**(THREE/TWO))*TWO*ERS/(ERS+ONE)                    FSTB0022
      DX=1.0D-2                                                         FSTB0023
      DY=5.0D0                                                          FSTB0024
      IF(FAC.LE.DX) GO TO 2                                             FSTB0025
      IF(FAC.GE.5.0D-2) GO TO 3                                         FSTB0026
      DO 1 I=1,5                                                        FSTB0027
      FAC1=DX*FLOAT(I)                                                  FSTB0028
      X=FAC-FAC1                                                        FSTB0029
      IF(X.GE.ZERO) GO TO 1                                             FSTB0030
      IX1=I-1                                                           FSTB0031
      IX2=I                                                             FSTB0032
      DIFX=FAC-DX*FLOAT(IX1)                                            FSTB0033
      GO TO 4                                                           FSTB0034
    1 CONTINUE                                                          FSTB0035
    2 IX1=1                                                             FSTB0036
      IX2=2                                                             FSTB0037
      DIFX=ZERO                                                         FSTB0038
      GO TO 4                                                           FSTB0039
    3 IX1=4                                                             FSTB0040
      IX2=5                                                             FSTB0041
      DIFX=DX                                                           FSTB0042
    4 CONTINUE                                                          FSTB0043
      IF(THW.LE.DY) GO TO 6                                             FSTB0044
      IF(THW.GE.45.0D0) GO TO 7                                         FSTB0045
      DO 5 J=1,9                                                        FSTB0046
      PSI1=DY*FLOAT(J)                                                  FSTB0047
      Y=THW-PSI1                                                        FSTB0048
      IF(Y.GE.ZERO) GO TO 5                                             FSTB0049
      JY1=J-1                                                           FSTB0050
      JY2=J                                                             FSTB0051
      DIFY=THW-DY*FLOAT(JY1)                                            FSTB0052
      GO TO 8                                                           FSTB0053
    5 CONTINUE                                                          FSTB0054
    6 JY1=1                                                             FSTB0055
      JY2=2                                                             FSTB0056
      DIFY=ZERO                                                         FSTB0057
      GO TO 8                                                           FSTB0058
    7 JY1=8                                                             FSTB0059
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```
      JY2=9
      DIFY=DY
    8 CONTINUE
      F1=TABLH(IX1,JY1)
      F2=TABLH(IX2,JY1)
      F3=TABLH(IX1,JY2)
      F4=TABLH(IX2,JY2)
      H=F1+DIFX/DX*(F2-F1)+DIFY/DY*(F3-F1)+DIFY*DIFX/(DY*DX)*(F4-
     1F3-F2+F1)
      H=H*DX
      STB=H/(TWO*FLOAT(B)*ERS*ERTE)
      THW=THW/RADEG
      RETURN
      END
C
C
C     FUNCTION LTB FOR COMPUTING THE TRANSFER INDUCTANCES FOR
C     BRAIDED SHIELDS
C
C
      REAL FUNCTION LTB*8(RS,RB,THW,B,WPB)
      IMPLICIT REAL*8 (A-H,O-Z)
      INTEGER B,WPB
      REAL*4 TABLG(5,9)
      REAL*8 MU,MUO2PI,MUO4PI
      COMMON /BCON/ ZERO,ONE,TWO,THREE,FOUR,MU,MUO2PI,MUO4PI,
     1PI,RADEG,ERTE,SIGCOP,R,F,V2
      DATA TABLG/.539,1.091,1.657,2.236,2.829,.555,1.117,1.686,
     12.261,2.844,.584,1.173,1.767,2.366,2.969,.621,1.246,1.874,2.507,
     23.143,.667,1.337,2.010,2.687,3.368,.727,1.457,2.190,2.928,
     33.668,.807,1.618,2.433,3.253,4.076,.910,1.825,2.745,3.671,
     44.603,1.045,2.098,3.158,4.226,5.303/
      THW=THW*RADEG
      XF=FLOAT(B)*FLOAT(WPB)*TWO*RB/(FOUR*PI*RS*DCOS(THW/RADEG))
      OPC=TWO*XF-XF*XF
      FAC=(ONE-OPC)**(THREE/TWO)
      DX=1.0D-2
      DY=5.0D0
      IF(FAC.LE.DX) GO TO 2
      IF(FAC.GE.5.0D-2) GO TO 3
      DO 1 I=1,5
      FAC1=DX*FLOAT(I)
      X=FAC-FAC1
      IF(X.GE.ZERO) GO TO 1
      IX1=I-1
      IX2=I
      DIFX=FAC-DX*FLOAT(IX1)
      GO TO 4
    1 CONTINUE
    2 IX1=1
      IX2=2
      DIFX=ZERO
      GO TO 4
    3 IX1=4
      IX2=5
      DIFX=DX
    4 CONTINUE
      IF(THW.LE.DY) GO TO 6
      IF(THW.GE.45.0D0) GO TO 7
      DO 5 J=1,9
      PSI1=DY*FLOAT(J)
```

```
      Y=THW-PSI1
      IF(Y.GE.ZERO) GO TO 5
      JY1=J-1
      JY2=J
      DIFY=THW-DY*FLOAT(JY1)
      GO TO 8
    5 CONTINUE
    6 JY1=1
      JY2=2
      DIFY=ZERO
      GO TO 8
    7 JY1=8
      JY2=9
      DIFY=DY
    8 CONTINUE
      F1=TABLG(IX1,JY1)
      F2=TABLG(IX2,JY1)
      F3=TABLG(IX1,JY2)
      F4=TABLG(IX2,JY2)
      XG=F1+DIFX/DX*(F2-F1)+DIFY/DY*(F3-F1)+DIFY*DIFX/(DX*DY)*(F4-F3-
     1F2+F1)
      XG=XG*DX
      LTB=MU*XG/(TWO*FLOAT(B))
      THW=THW/RADEG
      RETURN
      END
C
C
C     FUNCTION ZWW FOR COMPUTING THE SELF IMPEDANCES OF STRANDED WIRES
C
C
      COMPLEX FUNCTION ZWW*16(RST,NST,SIG)
      IMPLICIT REAL*8 (A-H,O-Z)
      REAL*8 MU,MUO2PI,MUO4PI,LDC
      COMPLEX*16 ZEROC,ONEC,XJ,JOMEGA
      DATA P25/.25D0/,ONEP15/1.15D0/,P5/.5D0/,P15/.15D0/
      COMMON /RCON/ ZERO,ONE,TWO,THREE,FOUR,MU,MUO2PI,MUO4PI,
     1PI,RADEG,ERTE,SIGCOP,R,F,V2
      COMMON /CCON/ ZEROC,ONEC,XJ,JOMEGA
      DELTA=ONE/(TWO*PI*DSQRT(SIG*SIGCOP*F*MUO4PI))
      RDC=ONE/(PI*SIG*SIGCOP*RST*RST)
      LDC=MUO4PI/TWO
      IF(RST.LE.DELTA) GO TO 1
      IF(RST.GE.THREE*DELTA) GO TO 2
      ZWW=(P25*(RST/DELTA+THREE)*RDC+JOMEGA*(ONEP15-P15*RST/DELTA)*
     1LDC)/FLOAT(NST)
      GO TO 3
    1 ZWW=(RDC+JOMEGA*LDC)/FLOAT(NST)
      GO TO 3
    2 ZWW=(P5*RST*RDC/DELTA+JOMEGA*TWO*DELTA*LDC/RST)/FLOAT(NST)
    3 CONTINUE
      RETURN
      END
C
C
C     FUNCTION ZDB FOR COMPUTING THE DIFFUSION IMPEDANCES OF BRAIDED
C     SHIELDS
C
C
      COMPLEX FUNCTION ZDB*16(RS,RB,SIGB,THW,B,WPB)
      IMPLICIT REAL*8 (A-H,O-Z)
```

```
      INTEGER B,WPB
      REAL*8 MU,MUO2PI,MUO4PI
      COMPLEX*16 ZEROC,ONEC,XJ,JOMEGA,GAM,SINH
      COMMON /RCON/ ZERO,ONE,TWO,THREE,FOUR,MU,MUO2PI,MUO4PI,
     1PI,RADEG,ERTE,SIGCOP,R,F,V2
      COMMON /CCON/ ZEROC,ONEC,XJ,JOMEGA
      DELTA=ONE/DSQRT(PI*F*MU*SIGB*SIGCOP)
      GAM=(ONE+XJ)/DELTA
      D=TWO*RB
      SINH=(CDEXP(GAM*D)-CDEXP(-GAM*D))/TWO
      RDC=ONE/(PI*RB*RB*SIGB*SIGCOP*FLOAT(B)*FLOAT(WPB)*
     1DCOS(THW))
      ZDB=RDC*GAM*D/SINH
      RETURN
      END
C
C
C     FUNCTION ZSB FOR COMPUTING THE SELF IMPEDANCES OF BRAIDED SHIELDS
C
C
      COMPLEX FUNCTION ZSB*16(RS,RB,SIGB,THW,B,WPB)
      IMPLICIT REAL*8 (A-H,O-Z)
      INTEGER B,WPB
      REAL*8 MU,MUO2PI,MUO4PI,LDC
      COMPLEX*16 ZEROC,ONEC,XJ,JOMEGA
      COMMON /RCON/ ZERO,ONE,TWO,THREE,FOUR,MU,MUO2PI,MUO4PI,
     1PI,RADEG,ERTE,SIGCOP,R,F,V2
      COMMON /CCON/ ZEROC,ONEC,XJ,JOMEGA
      DATA P25/.25D0/,ONEP15/1.15D0/,P5/.5D0/,P15/.15D0/
      DELTA=ONE/(TWO*PI*DSQRT(SIGB*SIGCOP*F*MUO4PI))
      RDC=ONE/(PI*SIGB*SIGCOP*RB*RB)
      LDC=MUO4PI/TWO
      IF(RB.LE.DELTA) GO TO 1
      IF(RB.GE.THREE*DELTA) GO TO 2
      ZSB=(P25*(RB/DELTA+THREE)*RDC+JOMEGA*(ONEP15-P15*RB/DELTA)*
     1LDC)/(FLOAT(B)*FLOAT(WPB)*DCOS(THW))
      GO TO 3
    1 ZSB=(RDC+JOMEGA*LDC)/(FLOAT(B)*FLOAT(WPB)*DCOS(THW))
      GO TO 3
    2 ZSB=(P5*RB*RDC/DELTA+JOMEGA*TWO*DELTA*LDC/RB)/(FLOAT(B)*
     1FLOAT(WPB)*DCOS(THW))
    3 CONTINUE
      RETURN
      END
C
C
C     FUNCTION ZDS FOR COMPUTING THE DIFFUSION IMPEDANCES OF
C     SOLID SHIELDS
C
C
      COMPLEX FUNCTION ZDS*16(RS,TS,SIGS)
      IMPLICIT REAL*8 (A-H,O-Z)
      REAL*8 MU,MUO2PI,MUO4PI
      COMPLEX*16 ZEROC,ONEC,XJ,JOMEGA,GAM,SINH
      COMMON /RCON/ ZERO,ONE,TWO,THREE,FOUR,MU,MUO2PI,MUO4PI,
     1PI,RADEG,ERTE,SIGCOP,R,F,V2
      COMMON /CCON/ ZEROC,ONEC,XJ,JOMEGA
      DELTA=ONE/DSQRT(PI*F*MU*SIGS*SIGCOP)
      GAM=(ONE+XJ)/DELTA
      RDC=ONE/(TWO*PI*SIGS*SIGCOP*TS*(RS-TS/TWO))
      SINH=(CDEXP(GAM*TS)-CDEXP(-GAM*TS))/TWO
```

```
      ZDS=RDC*GAM*TS/SINH                                               FZDS0018
      RETURN                                                            FZDS0019
      END                                                               FZDS0020
C                                                                       FZSS0001
C                                                                       FZSS0002
C     FUNCTION ZSS FOR COMPUTING THE SELF IMPEDANCES OF                 FZSS0003
C     SOLID SHIELDS                                                     FZSS0004
C                                                                       FZSS0005
C                                                                       FZSS0006
      COMPLEX FUNCTION ZSS*16(RS,TS,SIGS)                               FZSS0007
      IMPLICIT REAL*8 (A-H,O-Z)                                         FZSS0008
      REAL*8 MU,MUO2PI,MUO4PI                                           FZSS0009
      COMPLEX*16 ZEROC,ONEC,XJ,JOMEGA                                   FZSS0010
      COMMON /RCON/ ZERO,ONE,TWO,THREE,FOUR,MU,MUO2PI,MUO4PI,           FZSS0011
     1PI,RADEG,ERTE,SIGCOP,R,F,V2                                       FZSS0012
      COMMON /CCON/ ZEROC,ONEC,XJ,JOMEGA                                FZSS0013
      DELTA=ONE/DSQRT(PI*F*MU*SIGS*SIGCOP)                              FZSS0014
      RSS=ONE/(SIGS*SIGCOP*DELTA)                                       FZSS0015
      COSH=(DEXP(TWO*TS/DELTA)+DEXP(-TWO*TS/DELTA))/TWO                 FZSS0016
      SINH=(DEXP(TWO*TS/DELTA)-DEXP(-TWO*TS/DELTA))/TWO                 FZSS0017
      RR=RSS*((SINH+DSIN(TWO*TS/DELTA))/(COSH-DCOS(TWO*TS/DELTA)))/     FZSS0018
     1(TWO*PI*(RS-TS/TWO))                                              FZSS0019
      OLI=RSS*((SINH-DSIN(TWO*TS/DELTA))/(COSH-DCOS(TWO*TS/DELTA)))/    FZSS0020
     1(TWO*PI*(RS-TS/TWO))                                              FZSS0021
      ZSS=RR+XJ*OLI                                                     FZSS0022
      RETURN                                                            FZSS0023
      END                                                               FZSS0024
C                                                                       SMUL0001
C                                                                       SMUL0002
C     SUBROUTINE MULTC FOR MULTIPLYING TWO COMPLEX MATRICES             SMUL0003
C                                                                       SMUL0004
C                                                                       SMUL0005
      SUBROUTINE MULTC(A,B,C,NL,NM,NR)                                  SMUL0006
      IMPLICIT REAL*8 (A-H,O-Z)                                         SMUL0007
      COMPLEX*16 A(NL,NR),B(NL,NM),C(NM,NR),SUMC,ZEROC,ONEC,XJ,JOMEGA   SMUL0008
      COMMON /CCON/ZEROC,ONEC,XJ,JOMEGA                                 SMUL0009
      DO 2 I=1,NL                                                       SMUL0010
      DO 2 J=1,NR                                                       SMUL0011
      SUMC=ZEROC                                                        SMUL0012
      DO 1 K=1,NM                                                       SMUL0013
    1 SUMC=SUMC+B(I,K)*C(K,J)                                           SMUL0014
    2 A(I,J)=SUMC                                                       SMUL0015
      RETURN                                                            SMUL0016
      END                                                               SMUL0017
C                                                                       SCAP0001
C                                                                       SCAP0002
C     SUBROUTINE SCAP FOR COMPUTING THE INVERSE OF THE CAPACITANCE      SCAP0003
C     MATRIX                                                            SCAP0004
C                                                                       SCAP0005
C                                                                       SCAP0006
      SUBROUTINE SCAP(SS,IND,NU,NS,NT,NUPS,KEY,NNU,NNS)                 SCAP0007
      IMPLICIT REAL*8 (A-H,O-Z)                                         SCAP0008
      INTEGER KEY(NNS)                                                  SCAP0009
      REAL*8 IND(NT,NT),SS(NT,NT)                                       SCAP0010
      V=2.997925D8                                                      SCAP0011
      V2=V*V                                                            SCAP0012
      DO 1 I=1,NT                                                       SCAP0013
      DO 1 J=1,NT                                                       SCAP0014
    1 SS(I,J)=V2*IND(I,J)                                               SCAP0015
      IF(NS.EQ.0) GO TO 4                                               SCAP0016
      DO 3 I=1,NS                                                       SCAP0017
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```
      IF(KEY(I).EQ.2) GO TO 2                                           SCAP0018
      SS(I+NUPS,I+NUPS)=SS(I+NU,I+NU)                                   SCAP0019
    2 CONTINUE                                                          SCAP0020
    3 CONTINUE                                                          SCAP0021
    4 CONTINUE                                                          SCAP0022
      RETURN                                                            SCAP0023
      END                                                               SCAP0024
C                                                                       SIND0001
C                                                                       SIND0002
C     SUBROUTINE INDUCT FOR COMPUTING THE INDUCTANCE MATRIX             SIND0003
C                                                                       SIND0004
C                                                                       SIND0005
      SUBROUTINE INDUCT(IND,NU,NS,NT,NUPS,NTYPE,RW,YW,ZW,RS,YS,ZS,      SIND0006
     1RWP,YP,ZP,RWH,KEY,NNU,NNS)                                        SIND0007
      IMPLICIT REAL*8 (A-H,O-Z)                                         SIND0008
      INTEGER KEY(NNS)                                                  SIND0009
      REAL*8 MU,MUO2PI,MUO4PI                                           SIND0010
      REAL*8 IND(NT,NT),RW(NNU),YW(NNU),RS(NNS),YS(NNS),RWH(NNS),       SIND0011
     1ZS(NNS),YP(NNS),ZW(NNU),ZP(NNS),RWP(NNS),LS1,LM1,LS2,LM2          SIND0012
      COMMON /RCON/ ZERO,ONE,TWO,THREE,FOUR,MU,MUO2PI,MUO4PI,           SIND0013
     1PI,RADEG,ERTE,SIGCOP,R,F,V2                                       SIND0014
      GO TO (1,29), NTYPE                                               SIND0015
    1 CONTINUE                                                          SIND0016
      IF(NU.EQ.0) GO TO 3                                               SIND0017
      DO 2 I=1,NU                                                       SIND0018
    2 IND(I,I)=LS1(RW(I),YW(I))                                         SIND0019
    3 CONTINUE                                                          SIND0020
      IF(NS.EQ.0) GO TO 8                                               SIND0021
      DO 7 I=1,NS                                                       SIND0022
      IKEY=KEY(I)                                                       SIND0023
      GO TO (4,5), IKEY                                                 SIND0024
    4 IND(I+NU,I+NU)=LS1(RS(I),YS(I))                                   SIND0025
      GO TO 6                                                           SIND0026
    5 IND(I+NU,I+NU)=LS1(RWP(I),YP(I))                                  SIND0027
    6 CONTINUE                                                          SIND0028
      IND(I+NUPS,I+NUPS)=LS1(RWH(I),YS(I))                              SIND0029
    7 CONTINUE                                                          SIND0030
    8 CONTINUE                                                          SIND0031
      IF(NU.EQ.0) GO TO 10                                              SIND0032
      NUM1=NU-1                                                         SIND0033
      DO 9 I=1,NUM1                                                     SIND0034
      IP1=I+1                                                           SIND0035
      DO 9 J=IP1,NU                                                     SIND0036
    9 IND(I,J)=LM1(YW(I),YW(J),ZW(I),ZW(J))                             SIND0037
   10 CONTINUE                                                          SIND0038
      IF(NS.EQ.0) GO TO 21                                              SIND0039
      NSM1=NS-1                                                         SIND0040
      DO 16 I=1,NSM1                                                    SIND0041
      IP1=I+1                                                           SIND0042
      DO 16 J=IP1,NS                                                    SIND0043
      IF(KEY(I).EQ.1.AND.KEY(J).EQ.1) NK=1                              SIND0044
      IF(KEY(I).EQ.1.AND.KEY(J).EQ.2) NK=2                              SIND0045
      IF(KEY(I).EQ.2.AND.KEY(J).EQ.1) NK=3                              SIND0046
      IF(KEY(I).EQ.2.AND.KEY(J).EQ.2) NK=4                              SIND0047
      GO TO (11,12,13,14), NK                                           SIND0048
   11 CONTINUE                                                          SIND0049
      IND(I+NU,J+NU)=LM1(YS(I),YS(J),ZS(I),ZS(J))                       SIND0050
      GO TO 15                                                          SIND0051
   12 IND(I+NU,J+NU)=LM1(YS(I),YP(J),ZS(I),ZP(J))                       SIND0052
      GO TO 15                                                          SIND0053
   13 IND(I+NU,J+NU)=LM1(YP(I),YS(J),ZP(I),ZS(J))                       SIND0054
```

```
      GO TO 15
   14 IND(I+NU,J+NU)=LM1(YP(I),YP(J),ZP(I),ZP(J))
   15 CONTINUE
      IND(I+NUPS,J+NUPS)=LM1(YS(I),YS(J),ZS(I),ZS(J))
   16 CONTINUE
      IF(NU.EQ.0) GO TO 20
      DO 19 I=1,NU
      DO 19 J=1,NS
      IF(KEY(J).EQ.2) GO TO 17
      IND(I,J+NU)=LM1(YW(I),YS(J),ZW(I),ZS(J))
      GO TO 18
   17 CONTINUE
      IND(I,J+NU)=LM1(YW(I),YP(J),ZW(I),ZP(J))
   18 CONTINUE
      IND(I,J+NUPS)=LM1(YW(I),YS(J),ZW(I),ZS(J))
   19 CONTINUE
   20 CONTINUE
   21 CONTINUE
      IF(NS.EQ.0) GO TO 28
      DO 27 I=1,NS
      IF(KEY(I).EQ.2) GO TO 24
      IND(I+NU,I+NUPS)=LS1(RS(I),YS(I))
      DO 23 J=1,NS
      IF(I.EQ.J) GO TO 22
      IND(I+NU,J+NUPS)=LM1(YS(I),YS(J),ZS(I),ZS(J))
   22 CONTINUE
   23 CONTINUE
      GO TO 26
   24 CONTINUE
      DO 25 J=1,NS
   25 IND(I+NU,J+NUPS)=LM1(YP(I),YS(J),ZP(I),ZS(J))
   26 CONTINUE
   27 CONTINUE
   28 CONTINUE
      GO TO 57
   29 CONTINUE
      IF(NU.EQ.0) GO TO 31
      DO 30 I=1,NU
   30 IND(I,I)=LS2(RW(I),YW(I))
   31 CONTINUE
      IF(NS.EQ.0) GO TO 36
      DO 35 I=1,NS
      IKEY=KEY(I)
      GO TO (32,33), IKEY
   32 IND(I+NU,I+NU)=LS2(RS(I),YS(I))
      GO TO 34
   33 IND(I+NU,I+NU)=LS2(RWP(I),YP(I))
   34 CONTINUE
      IND(I+NUPS,I+NUPS)=LS2(RWH(I),YS(I))
   35 CONTINUE
   36 CONTINUE
      IF(NU.EQ.0) GO TO 38
      NUM1=NU-1
      DO 37 I=1,NUM1
      IP1=I+1
      DO 37 J=IP1,NU
   37 IND(I,J)=LM2(YW(I),YW(J),ZW(I),ZW(J))
   38 CONTINUE
      IF(NS.EQ.0) GO TO 49
      NSM1=NS-1
      DO 44 I=1,NSM1
```

```
      IP1=I+1
      DO 44 J=IP1,NS
      IF(KEY(I).EQ.1.AND.KEY(J).EQ.1)  NK=1
      IF(KEY(I).EQ.1.AND.KEY(J).EQ.2)  NK=2
      IF(KEY(I).EQ.2.AND.KEY(J).EQ.1)  NK=3
      IF(KEY(I).EQ.2.AND.KEY(J).EQ.2)  NK=4
      GO TO (39,40,41,42), NK
   39 CONTINUE
      IND(I+NU,J+NU)=LM2(YS(I),YS(J),ZS(I),ZS(J))
      GO TO 43
   40 IND(I+NU,J+NU)=LM2(YS(I),YP(J),ZS(I),ZP(J))
      GO TO 43
   41 IND(I+NU,J+NU)=LM2(YP(I),YS(J),ZP(I),ZS(J))
      GO TO 43
   42 IND(I+NU,J+NU)=LM2(YP(I),YP(J),ZP(I),ZP(J))
   43 CONTINUE
      IND(I+NUPS,J+NUPS)=LM2(YS(I),YS(J),ZS(I),ZS(J))
   44 CONTINUE
      IF(NU.EQ.0)  GO TO 48
      DO 47 I=1,NU
      DO 47 J=1,NS
      IF(KEY(J).EQ.2)  GO TO 45
      IND(I,J+NU)=LM2(YW(I),YS(J),ZW(I),ZS(J))
      GO TO 46
   45 CONTINUE
      IND(I,J+NU)=LM2(YW(I),YP(J),ZW(I),ZP(J))
   46 CONTINUE
      IND(I,J+NUPS)=LM2(YW(I),YS(J),ZW(I),ZS(J))
   47 CONTINUE
   48 CONTINUE
   49 CONTINUE
      IF(NS.EQ.0)  GO TO 56
      DO 55 I=1,NS
      IF(KEY(I).EQ.2)  GO TO 52
      IND(I+NU,I+NUPS)=LS2(RS(I),YS(I))
      DO 51 J=1,NS
      IF(I.EQ.J)  GO TO 50
      IND(I+NU,J+NUPS)=LM2(YS(I),YS(J),ZS(I),ZS(J))
   50 CONTINUE
   51 CONTINUE
      GO TO 54
   52 CONTINUE
      DO 53 J=1,NS
   53 IND(I+NU,J+NUPS)=LM2(YP(I),YS(J),ZP(I),ZS(J))
   54 CONTINUE
   55 CONTINUE
   56 CONTINUE
   57 CONTINUE
      DO 58 I=2,NT
      IM1=I-1
      DO 58 J=1,IM1
   58 IND(I,J)=IND(J,I)
      RETURN
      END
C
C
C     SUBROUTINE PHI FOR COMPUTING THE CHAIN PARAMETER MATRICES
C
C
      SUBROUTINE PHI(PHIT,NT,TNT,LMIN,GAM,Y,YINV,T,TI,EP,EN)
      IMPLICIT REAL*8 (A-H,O-Z)
```

```
      INTEGER TNT
      REAL*8 LMIN
      COMPLEX*16 PHIT(TNT,TNT),GAM(NT),Y(NT,NT),YINV(NT,NT),T(NT,NT),
     1TI(NT,NT),EP(NT),EN(NT)
      COMPLEX*16 ZEROC,ONEC,XJ,JOMEGA,SUMC,SUMC1,SUMC2
      COMMON /CCON/ ZEROC,ONEC,XJ,JOMEGA
      TWO=2.D0
      DO 1 I=1,NT
      EP(I)=CDEXP(GAM(I)*LMIN)
    1 EN(I)=CDEXP(-GAM(I)*LMIN)
      DO 3 I=1,NT
      DO 3 J=1,NT
      SUMC=ZEROC
      SUMC1=ZEROC
      SUMC2=ZEROC
      DO 2 K=1,NT
      SUMC1=SUMC1+T(I,K)*(EP(K)+EN(K))*TI(K,J)/TWO
      SUMC2=SUMC2+T(I,K)*GAM(K)*(EP(K)-EN(K))*TI(K,J)/TWO
    2 SUMC=SUMC+T(I,K)*(EP(K)-EN(K))*TI(K,J)/(TWO*GAM(K))
      PHIT(I,J)=SUMC1
      PHIT(I,J+NT)=-SUMC2
      PHIT(I+NT,J)=-SUMC
    3 PHIT(I+NT,J+NT)=SUMC1
      DO 5 I=1,NT
      DO 5 J=1,NT
      SUMC=ZEROC
      SUMC1=ZEROC
      DO 4 K=1,NT
      SUMC=SUMC+YINV(I,K)*PHIT(K,J)
    4 SUMC1=SUMC1+YINV(I,K)*PHIT(K,J+NT)
      T(I,J)=SUMC
    5 TI(I,J)=SUMC1
      DO 7 I=1,NT
      DO 7 J=1,NT
      SUMC=ZEROC
      SUMC1=ZEROC
      DO 6 K=1,NT
      SUMC=SUMC+T(I,K)*Y(K,J)
    6 SUMC1=SUMC1+PHIT(I+NT,K)*Y(K,J)
      PHIT(I,J)=SUMC
    7 YINV(I,J)=SUMC1
      DO 8 I=1,NT
      DO 8 J=1,NT
      PHIT(I,J+NT)=TI(I,J)
    8 PHIT(I+NT,J)=YINV(I,J)
      RETURN
      END
C
C
C     SUBROUTINE ADMADD FOR ADDING ELASTANCES TO THE INVERSE
C     OF THE CAPACITANCE MATRIX
C
C
      SUBROUTINE ADMADD(KEY,NU,NS,NT,NUPS,RS,TS,RWH,ERS,SS,STV,NNU,NNS)
      IMPLICIT REAL*8 (A-H,O-Z)
      INTEGER KEY(NNS)
      REAL*8 MU,MUO2PI,MUO4PI
      REAL*8 RS(NNS),TS(NNS),RWH(NNS),ERS(NNS),SS(NT,NT),STV(NNS)
      COMMON /BCON/ ZERO,ONE,TWO,THREE,FOUR,MU,MUO2PI,MUO4PI,
     1PI,RADEG,ERTE,SIGCOP,R,F,V2
      IF(NS.EQ.0) GO TO 4
```

```
      DO 3 I=1,NS
      IF(KEY(I).EQ.2) GO TO 1
      STRAN=STV(I)
      SWW=DLOG((RS(I)-TS(I))/RWH(I))/(TWO*PI*ERS(I)*ERTE)
      GO TO 2
    1 CONTINUE
      STRAN=ZERO
      SWW=ZERO
    2 CONTINUE
      SS(I+NU,I+NUPS)=SS(I+NU,I+NUPS)+STRAN
      SS(I+NUPS,I+NU)=SS(I+NUPS,I+NU)+STRAN
      SS(I+NUPS,I+NUPS)=SS(I+NUPS,I+NUPS)+SWW+STRAN
    3 CONTINUE
    4 CONTINUE
      RETURN
      END
C
C
C     SUBROUTINE IMPADD FOR ADDING IMPEDANCES TO THE IMPEDANCE
C     MATRIX
C
C
      SUBROUTINE IMPADD(Z,KEY,NU,NS,NT,NUPS,ZSV,ZDV,LTV,ZWPLV,ZWWHV,
     1NNU,NNS)
      IMPLICIT REAL*8 (A-H,O-Z)
      REAL*8 MU,MUO2PI,MUO4PI,LTRAN,LTB
      COMPLEX*16 ZEROC,ONEC,XJ,JOMEGA
      INTEGER KEY(NNS)
      REAL*8 LTV(NNS)
      COMPLEX*16 ZSELF,ZDIF,Z(NT,NT),ZSV(NNS),ZDV(NNS),ZWPLV(NNS),
     1ZWWHV(NNS)
      COMMON /RCON/ ZERO,ONE,TWO,THREE,FOUR,MU,MUO2PI,MUO4PI,
     1PI,RADEG,ERTE,SIGCOP,R,F,V2
      COMMON /CCON/ ZEROC,ONEC,XJ,JOMEGA
      IF(NS.EQ.0) GO TO 4
      DO 3 I=1,NS
      IF(KEY(I).EQ.2) GO TO 1
      ZSELF=ZSV(I)
      ZDIF=ZDV(I)
      LTRAN=LTV(I)
      GO TO 2
    1 CONTINUE
      ZSELF=ZWPLV(I)
      ZDIF=ZSELF
      LTRAN=ZERO
    2 CONTINUE
      Z(I+NU,I+NU)=Z(I+NU,I+NU)+ZSELF
      Z(I+NU,I+NUPS)=Z(I+NU,I+NUPS)+ZSELF-ZDIF-JOMEGA*LTRAN
      Z(I+NUPS,I+NU)=Z(I+NUPS,I+NU)+ZSELF-ZDIF-JOMEGA*LTRAN
      Z(I+NUPS,I+NUPS)=Z(I+NUPS,I+NUPS)+TWO*(ZSELF-ZDIF-JOMEGA*LTRAN)
     1+ZWWHV(I)
    3 CONTINUE
    4 CONTINUE
      RETURN
      END
```

APPENDIX B

Conversion of SHIELD to Single Precision

Conversion of SHIELD to Single Precision

Delete 0038

Card	Double Precision	Single Precision
0039	REAL*8	REAL
0041	COMPLEX*16	COMPLEX
0063	REAL*8	REAL
0075	COMPLEX*16	COMPLEX
0090	REAL*8	REAL
0091	COMPLEX*16	COMPLEX
0103	REAL*8	REAL
0108	COMPLEX*16	COMPLEX
0117	0.0DO	0.0EO
0118	1.0DO	1.0EO
0119	2.0DO	2.0EO
0120	3.0DO	3.0EO
0121	4.0DO	4.0EO
0122	2.54D-5	2.54E-5
0123	2.D-7	2.E-7
0124	1.D-7	1.E-7
0125	180.DO	180.EO
0126	2.997925D8	2.997925E8
0127	5.8D-7	5.8E-7
0128	DCMPLX	CMPLX
0129	DCMPLX	CMPLX
0130	DCMPLX	CMPLX
0131	DATAN	ATAN

Card	Double Precision	Single Precision
0241	45.DO	45.EO
0345	DSIN	SIN
0346	DCOS	COS
0347	DSIN	SIN
0348	DCOS	COS
0351	DSQRT	SQRT
0351	DCOS	COS
0352	DATAN2	ATAN2
0352	DSIN	SIN
0353	DCOS	COS
0354	DSQRT	SQRT
0354	DCOS	COS
0355	DATAN2	ATAN2
0355	DSIN	SIN
0356	DCOS	COS
0530	DCMPLX	CMPLX
0609	DREAL	REAL
0620	CDSQRT	CSQRT
0680	DREAL	REAL
0691	CDSQRT	CSQRT
0735	DREAL	REAL
0746	CDSQRT	CSQRT
0774	DREAL	REAL
0785	CDSQRT	CSQRT
0931	CDABS	CABS

Card	Double Precision	Single Precision
0932	DREAL	REAL
0933	DIMAG	AIMAG
0934	DATAN2	ATAN2
0936	CDABS	CABS
0937	DREAL	REAL
0938	DIMAG	AIMAG
0939	DATAN2	ATAN2
0950	CDABS	CABS
0951	DREAL	REAL
0952	DIMAG	AIMAG
0953	DATAN2	ATAN2
0955	CDABS	CABS
0956	DREAL	REAL
0957	DIMAG	AIMAG
0958	DATAN2	ATAN2

FUNCTION LS1

0007	LS1*8	LS1
Delete 0008		
0009	REAL*8	REAL
0012	DLOG	ALOG

FUNCTION LM1

0007	LM1*8	LM1
Delete 0008		
0009	REAL*8	REAL
0015	DLOG	ALOG

FUNCTION LS2

0007	LS2*8	LS2
Delete 0008		
0009	REAL*8	REAL
0012	DLOG	ALOG

FUNCTION LM2

0007	LM2*8	LM2
Delete 0008		
0009	REAL*8	REAL
0016	DLOG	ALOG
0017	DCOS	COS
0017	DCOS	COS

FUNCTION STB

0007	STB*8	STB
Delete 0008		
0010	REAL*4	REAL
0011	REAL*8	REAL
0020	DCOS	COS
0023	1.0D-2	1.0E-2
0024	5.0DO	5.0EO
0026	5.0D-2	5.0E-2
0045	45.0DO	45.0EO

FUNCTION LTB

0007	LTB*8	LTB
Delete 0008		
0010	REAL*4	REAL
0011	REAL*8	REAL
0020	DCOS	COS
0023	1.0D-2	1.0E-2
0024	5.0D0	5.0E0
0026	5.0D-2	5.0E-2
0045	45.0D0	45.0E0

FUNCTION ZWW

0006	ZWW*16	ZWW
Delete 0007		
0008	REAL*8	REAL
0009	COMPLEX*16	COMPLEX
0010	Change all D's to E's	
0014	DSQRT	SQRT

FUNCTION ZDB

0007	ZDB*16	ZDB
Delete 0008		
0010	REAL*8	REAL
0011	COMPLEX*16	COMPLEX
0015	DSQRT	SQRT
0018	CDEXP	CEXP
0018	CDEXP	CEXP
0020	DCOS	COS

FUNCTION ZSB

0006	ZSB*16	ZSB
Delete 0007		
0009	REAL*8	REAL
0010	COMPLEX*16	COMPLEX
0014	Change all D's to E's	
0015	DSQRT	SQRT
0021	DCOS	COS
0023	DCOS	COS
0026	DCOS	COS

FUNCTION ZDS

0007	ZDS*16	ZDS
Delete 0008		
0009	REAL*8	REAL
0010	COMPLEX*16	COMPLEX
0014	DSQRT	SQRT
0017	CDEXP	CEXP
0017	CDEXP	CEXP

FUNCTION ZSS

0007	ZSS*16	ZSS
Delete 0008		
0009	REAL*8	REAL
0010	COMPLEX*16	COMPLEX
0014	DSQRT	SQRT
0016	DEXP	EXP
0016	DEXP	EXP

FUNCTION ZSS (Cont'd)

0017	DEXP	EXP
0017	DEXP	EXP
0018	DSIN	SIN
0018	DCOS	COS
0020	DSIN	SIN
0020	DCOS	COS

SUBROUTINE MULTC

Delete 0007

0008	COMPLEX*16	COMPLEX

SUBROUTINE SCAP

Delete 0008

0010	REAL*8	REAL
0011	2.997925D8	2.997925E8

SUBROUTINE INDUCT

Delete 0008

0010	REAL*8	REAL
0011	REAL*8	REAL

SUBROUTINE PHI

Delete 0007

0009	REAL*8	REAL
0010	COMPLEX*16	COMPLEX
0012	COMPLEX*16	COMPLEX
0014	2.DO	2.EO

SUBROUTINE PHI (Cont'd)

0016	CDEXP	CEXP
0017	CDEXP	CEXP

SUBROUTINE ADMADD

Delete 0008

0010	REAL*8	REAL
0011	REAL*8	REAL
0018	DLOG	ALOG

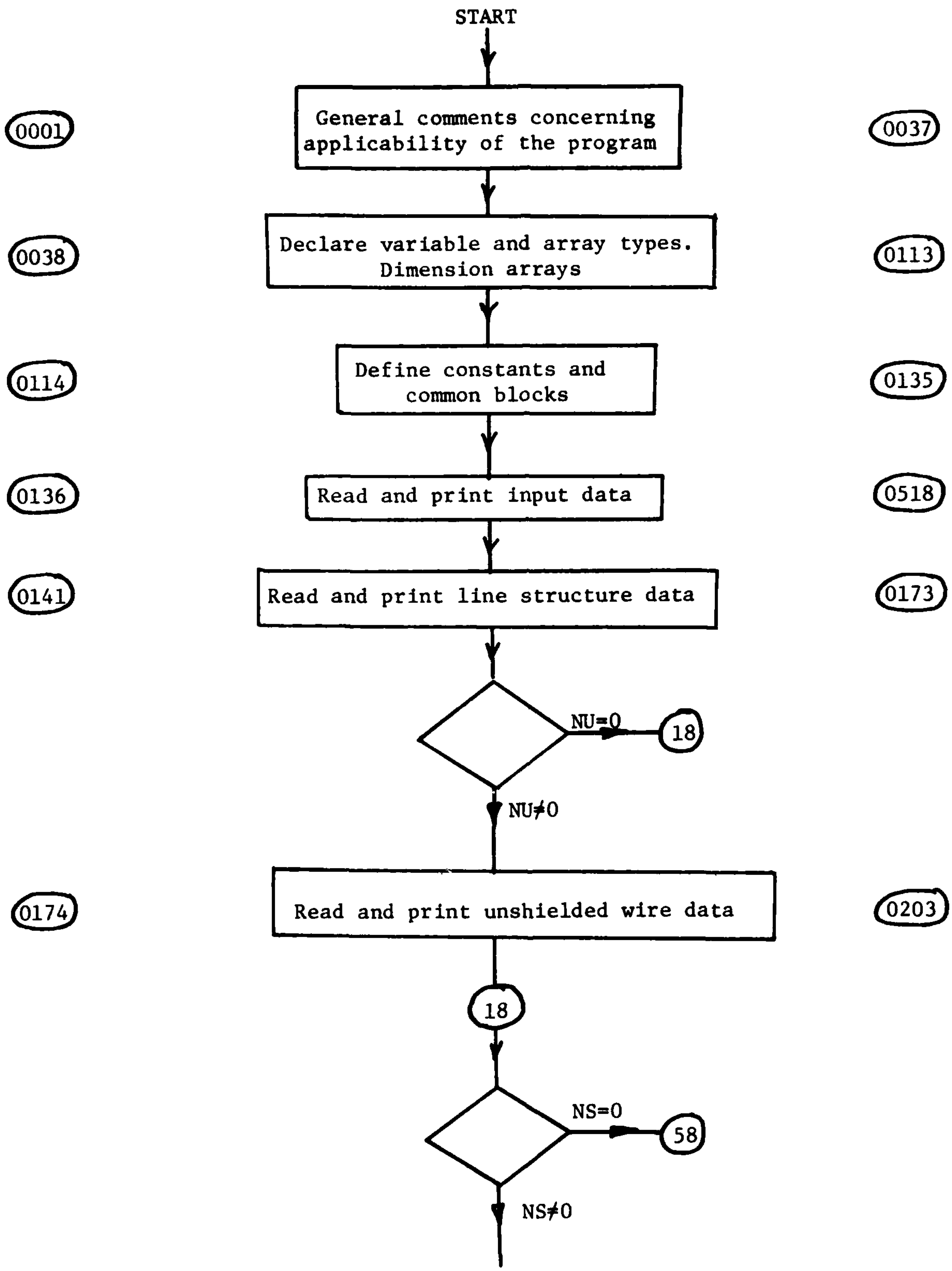
SUBROUTINE IMPADD

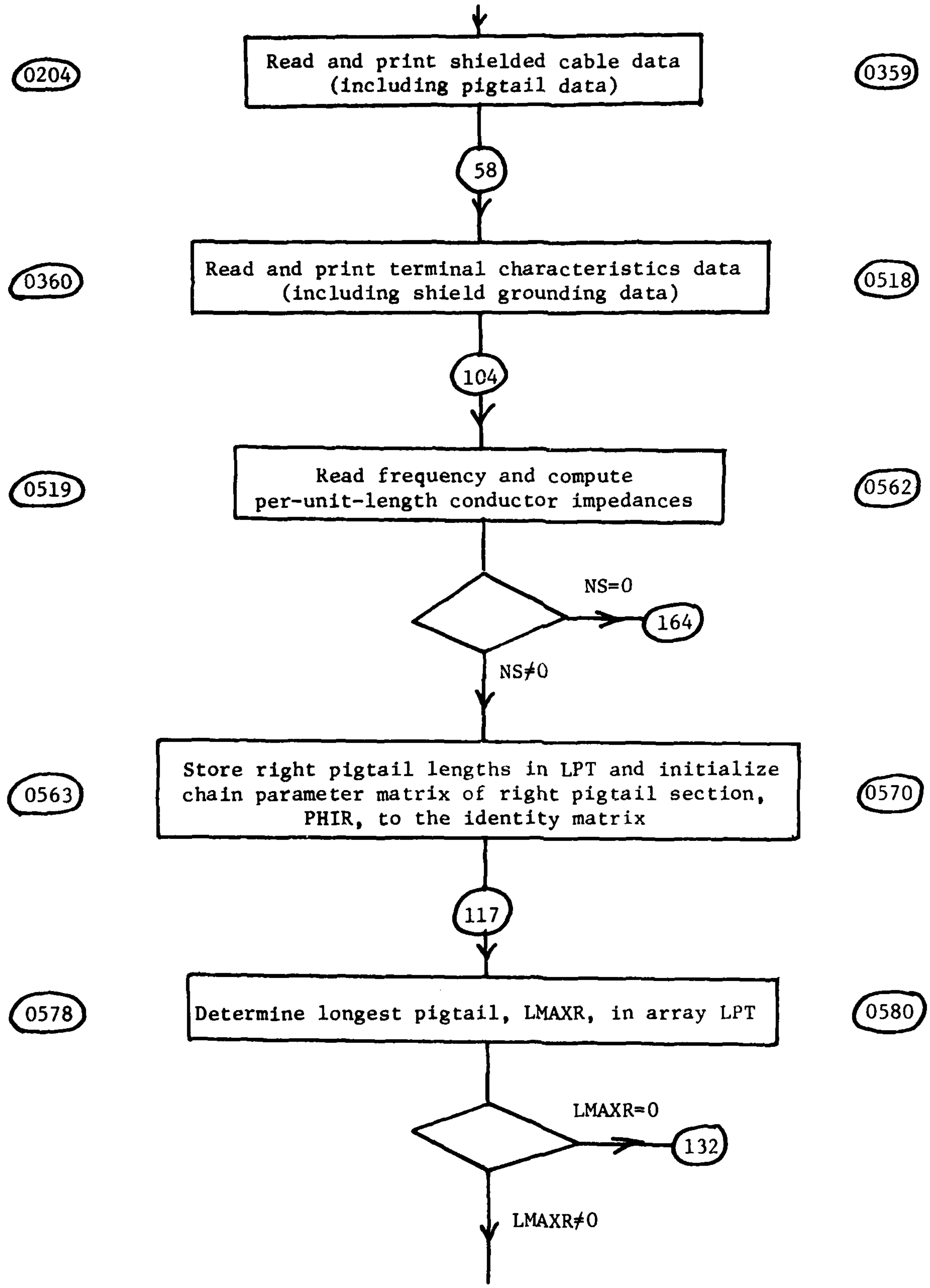
Delete 0009

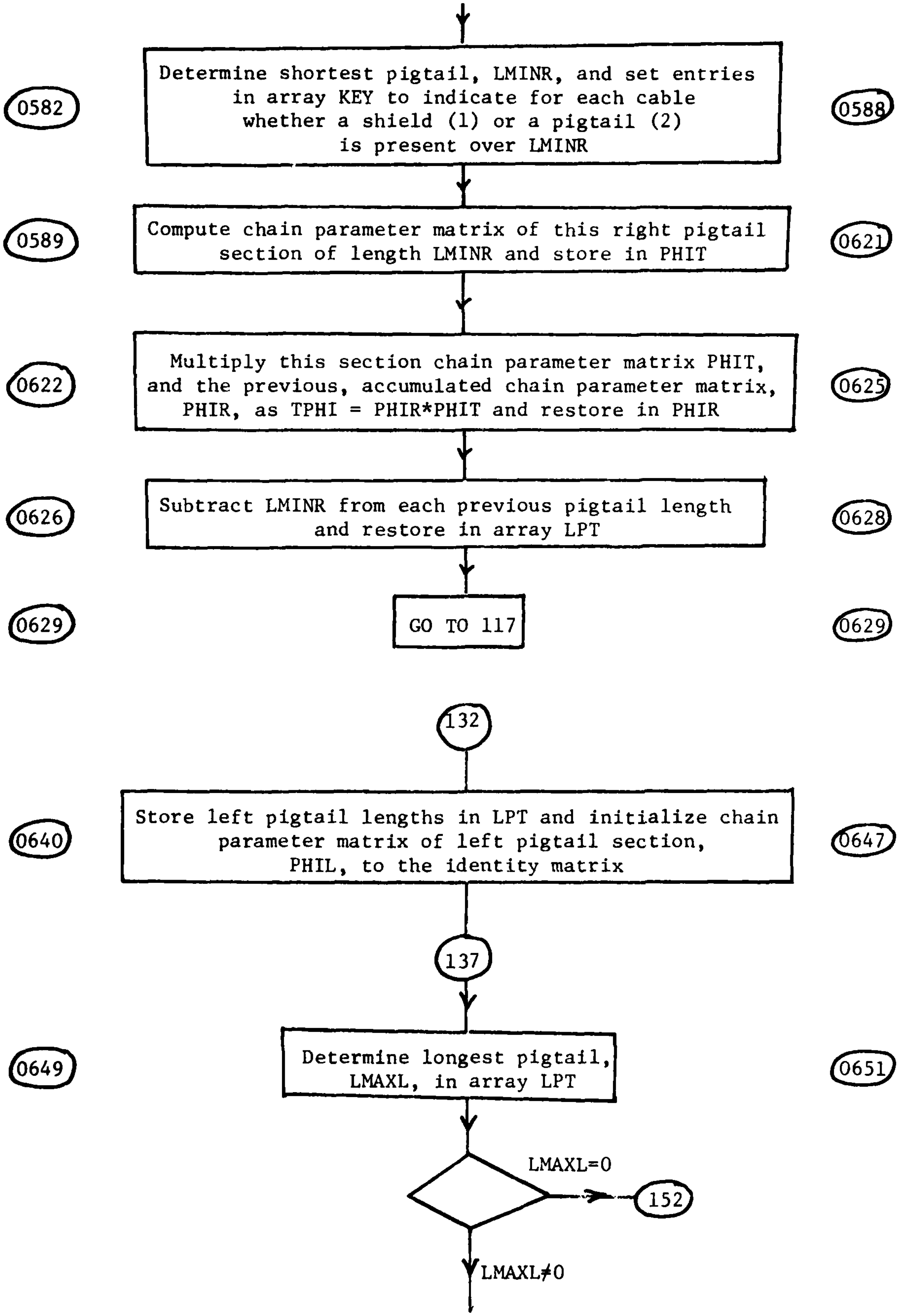
0010	REAL*8	REAL
0011	COMPLEX*16	COMPLEX
0013	REAL*8	REAL
0014	COMPLEX*16	COMPLEX

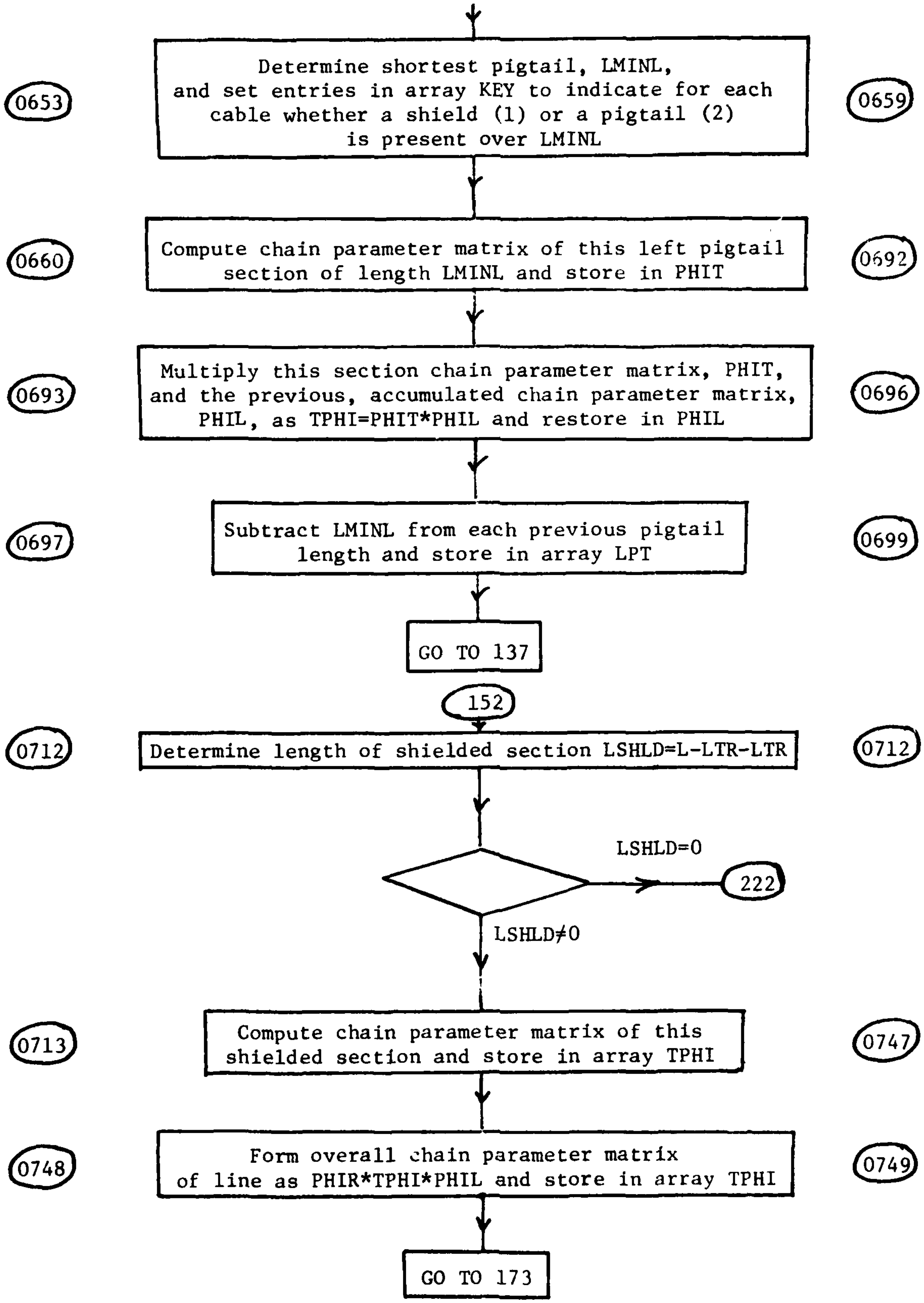
APPENDIX C

Flowchart of SHIELD

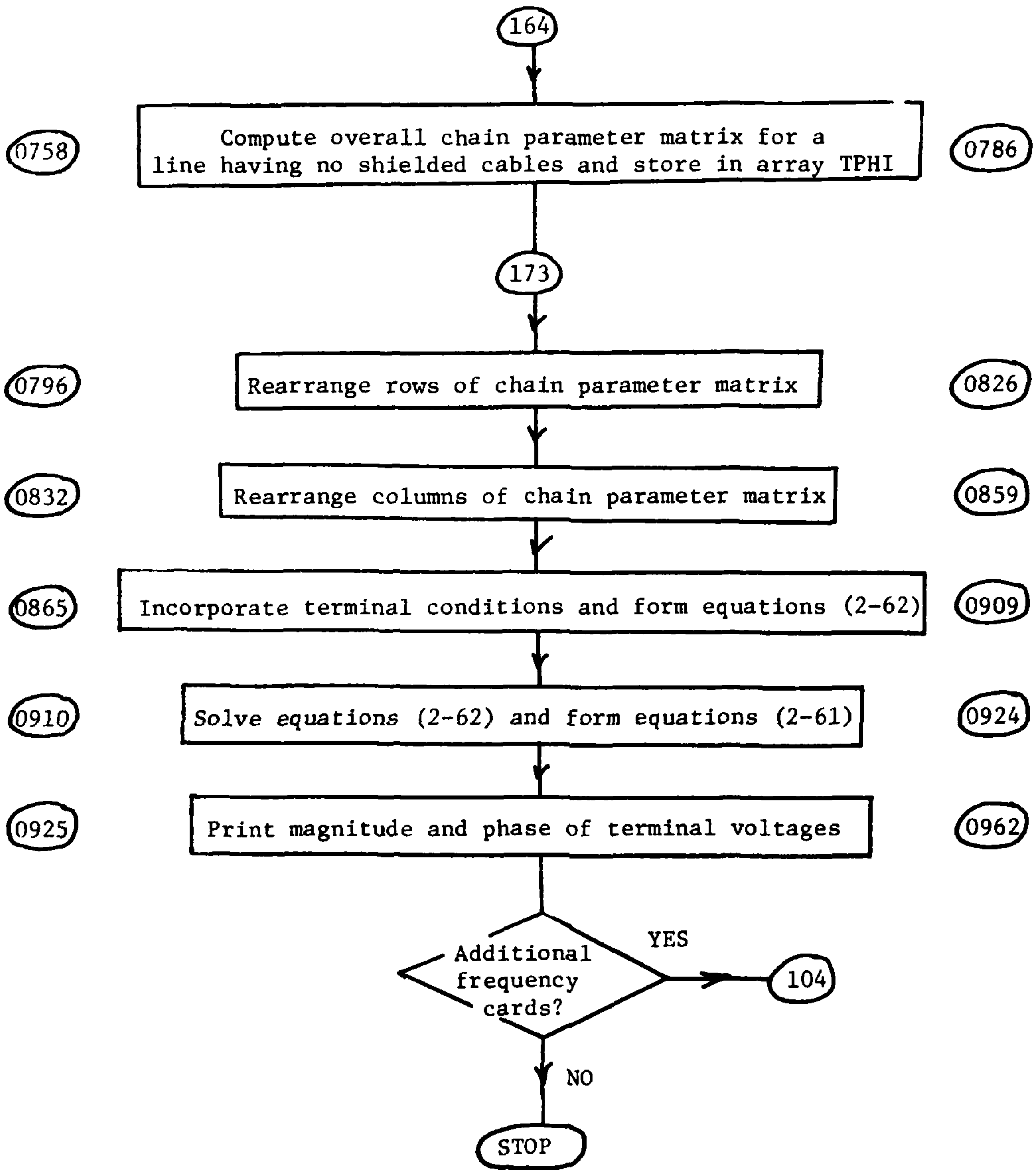

START
0001
General comments concerning applicability of the program
0037
0038
Declare variable and array types. Dimension arrays
0113
0114
Define constants and common blocks
0135
0136
Read and print input data
0518
0141
Read and print line structure data
0173
NU=0
18
NU≠0
0174
Read and print unshielded wire data
0203
18
NS=0
58
NS≠0


0204
Read and print shielded cable data (including pigtail data)
0359
58
0360
Read and print terminal characteristics data (including shield grounding data)
0518
104
0519
Read frequency and compute per-unit-length conductor impedances
0562
NS=0
164
NS≠0
0563
Store right pigtail lengths in LPT and initialize chain parameter matrix of right pigtail section, PHIR, to the identity matrix
0570
117
0578
Determine longest pigtail, LMAXR, in array LPT
0580
LMAXR=0
132
LMAXR≠0


0582
Determine shortest pigtail, LMINR, and set entries in array KEY to indicate for each cable whether a shield (1) or a pigtail (2) is present over LMINR
0588
0589
Compute chain parameter matrix of this right pigtail section of length LMINR and store in PHIT
0621
0622
Multiply this section chain parameter matrix PHIT, and the previous, accumulated chain parameter matrix, PHIR, as TPHI = PHIR*PHIT and restore in PHIR
0625
0626
Subtract LMINR from each previous pigtail length and restore in array LPT
0628
0629
GO TO 117
0629
132
0640
Store left pigtail lengths in LPT and initialize chain parameter matrix of left pigtail section, PHIL, to the identity matrix
0647
137
0649
Determine longest pigtail, LMAXL, in array LPT
0651
LMAXL=0
152
LMAXL≠0



Determine shortest pigtail, LMINL, and set entries in array KEY to indicate for each cable whether a shield (1) or a pigtail (2) is present over LMINL
0653
0659
Compute chain parameter matrix of this left pigtail section of length LMINL and store in PHIT
0660
0692
Multiply this section chain parameter matrix, PHIT, and the previous, accumulated chain parameter matrix, PHIL, as TPHI=PHIT*PHIL and restore in PHIL
0693
0696
Subtract LMINL from each previous pigtail length and store in array LPT
0697
0699
GO TO 137
152
Determine length of shielded section LSHLD=L-LTR-LTR
0712
0712
LSHLD=0
222
LSHLD≠0
Compute chain parameter matrix of this shielded section and store in array TPHI
0713
0747
Form overall chain parameter matrix of line as PHIR*TPHI*PHIL and store in array TPHI
0748
0749
GO TO 173



164
0758
Compute overall chain parameter matrix for a line having no shielded cables and store in array TPHI
0786
173
0796
Rearrange rows of chain parameter matrix
0826
0832
Rearrange columns of chain parameter matrix
0859
0865
Incorporate terminal conditions and form equations (2-62)
0909
0910
Solve equations (2-62) and form equations (2-61)
0924
0925
Print magnitude and phase of terminal voltages
0962
Additional frequency cards?
YES
104
NO
STOP

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