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USER'S MANUAL FOR THE NLINE MULTICONDUCTOR TRANSMISSION-LINE CO--ETC(U)
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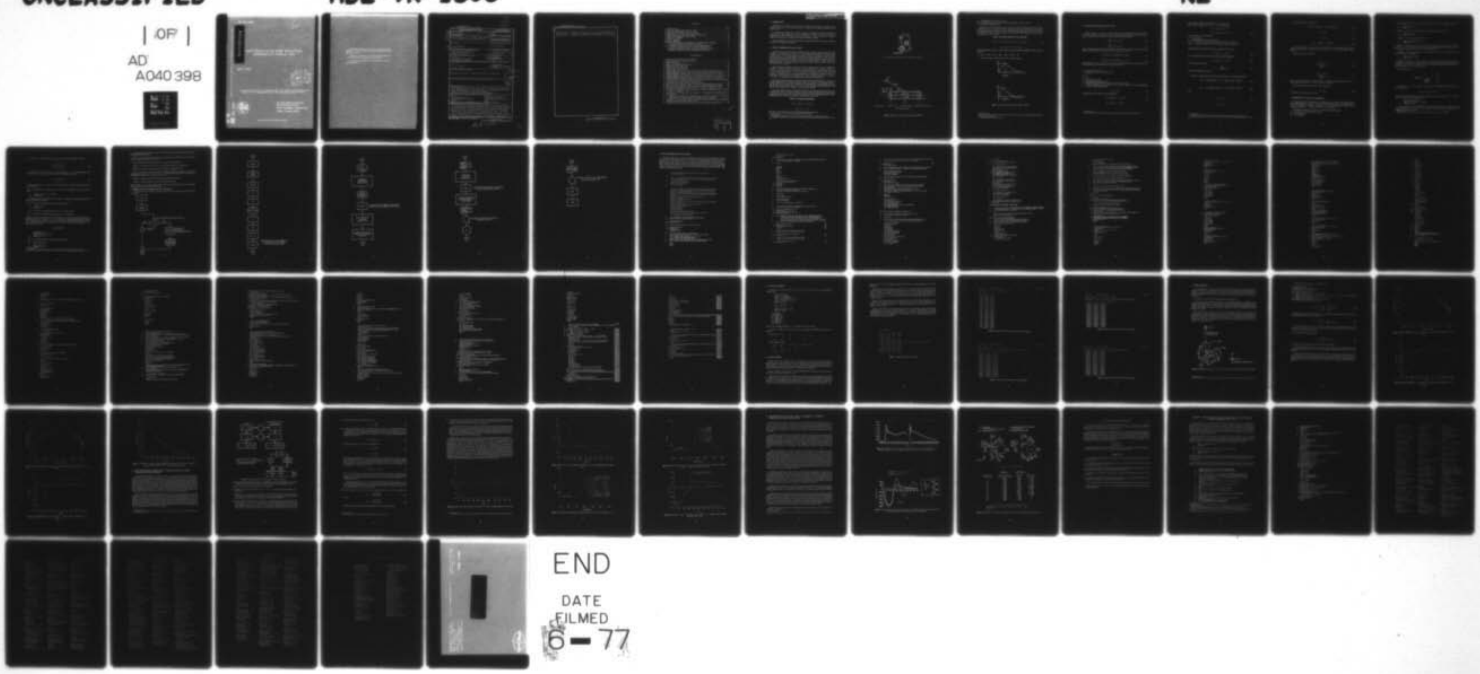

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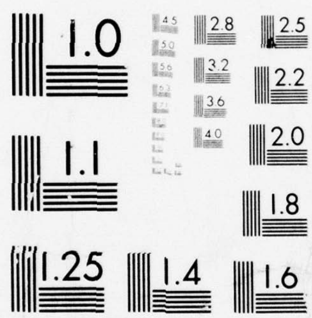

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HDL-TR-1803

User's Manual for the NLINE Multiconductor Transmission-Line Computer Code

MAY 1977

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WORK UNIT TITLE: "GROUND-BASED ANTENNA SYSTEM CHARACTERISTICS AND NLINE MANUAL."

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HARRY DIAMOND LABORATORIES
Adelphi, Maryland 20783

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19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

EMP
Transmission line
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Cables
Multiconductor transmission line
Distributed excitation of transmission lines
Transmission-line computer code
Computer methods

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This manual describes applications of the multiconductor transmission-line computer program, NLINE. The program computes the voltages and currents induced by an incident plane electromagnetic wave on the conductors or in the loads of a lossless transmission line made up of 11 conductors or less. The solution is provided both in the frequency and time domains. The program accepts arbitrary angles of incidence, transmission-line length, and resistive terminations. The Thévenin equivalent

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lumped-parameter method is described for use of NLINE with non-linear loads. Computational agreement with experimental data is demonstrated. A complete FORTRAN program listing is included.

CONTENTS

ILLUSTRATIONS

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1. INTRODUCTION

Applications of the multiconductor transmission-line computer program, NLINE, are described in this manual. Previous reports [1,2] have detailed theoretical development and semi-empirical methods on which NLINE is based.

It is assumed that the reader knows computer programming in FORTRAN. The annotated listing of the NLINE Standard Deck (NSD) given in section 6 represents the complete NLINE code. The NSD is compatible with the CDC 6600/6700 computers. If IBM computers are used, it is necessary to modify the alpha-numeric statements (*i.e.*, change dimensioning due to different word length).

It is recommended that an output plotting capability, compatible with the user's computer, be added to the NSD for most efficient output display.

2. TYPES OF PROBLEMS SOLVED BY NLINE

The NLINE code computes currents and voltages induced by a plane-wave electromagnetic pulse (EMP) impinging on the conductors and terminations of a lossless multiconductor transmission line. Computations are initially done in the frequency domain. Time-domain results are obtained by a numerical Fourier transform subroutine. The response depends on the physical and electrical characteristics of the transmission line and upon the orientation, pulse shape, and amplitude of the incident EMP. The transmission line may be located in free space or above a ground plane, and it is described by its length, l, conductor cross section, propagation velocity, v, terminating impedances, and choice of reference conductor. Figure 1 illustrates the above properties for a typical line.

The total number of conductors in the transmission line is designated here by n, and by "NWIRES" in the NSD. A convenient reference conductor (*e.g.*, the ground plane, if one is present) is chosen, and numbered 0, with the remaining (n-1) conductors numbered consecutively as shown in figure 1(a), where $n = 3$. The propagation velocity, v, for the transmission line is assumed to be known. As a matter of consistency, in this report the x-axis is always chosen parallel to the longitudinal axis of the line. The point of voltage and current computation is thus designated by a value of x within the limits $0 \leq x \leq l$. Values of $x = 0$ and $x = l$ give results at the terminations. Figure 1(b) illustrates these parameters.

Terminations between conductors are represented by the doubly subscripted variables, Z_{ij}, in figure 1(a). NLINE is programmed for all possible connections between the conductors. The termination values are assumed known, or must be measured or estimated (*e.g.*, assume open, short, or matched conditions) for the line. The NSD accepts only *real* values for the Z_{ij}. The *Thévenin Equivalent* method described later in this report may be used with NLINE if complex or nonlinear loads are required.

The incident EMP waveshape is represented in NLINE by two independent expressions made up of exponential terms. The user can choose either when making an NLINE run. In addition, the option of using a unit impulse as the input has been incorporated into the code. The first of the exponential pulse forms is designated as Pulse(1). This pulse is the familiar two-exponential form given below.

Pulse(1). Two-exponential representation

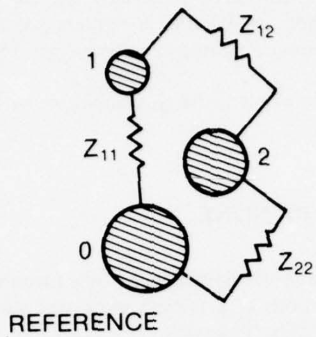
$$E_y^e(t) = A\left(e^{-\alpha_1 t} - e^{-\alpha_2 t}\right) / M \qquad (1)$$

$$M = e^{-\alpha_1 t_o} - e^{-\alpha_2 t_o}$$

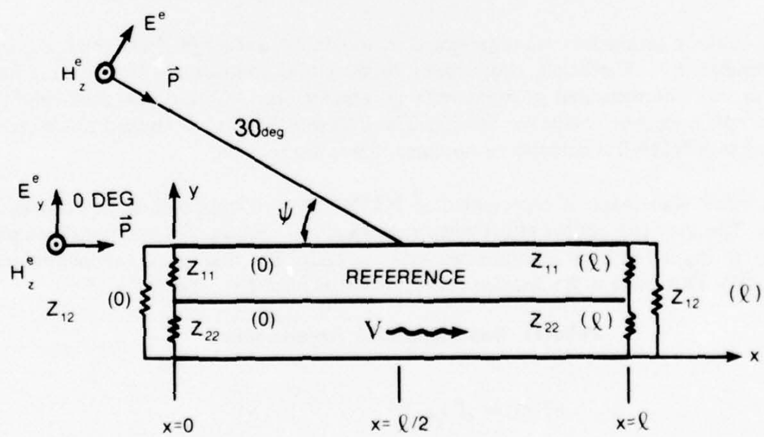
where $E_y^e(t)$ is the y-component of the incident EMP electric field in volts/meter.
$t_o = ln\,(\alpha_2/\alpha_1)\,/\,(\alpha_2 - \alpha_1)$ is the zero-to-peak rise time of the pulse.

[1] Sidney Frankel, *Cable and Multiconductor Transmission Line Analysis*, Harry Diamond Laboratories TR-091-1 (28 June 1974).

[2] Janis Klebers, *Electromagnetic Pulse Coupling with Lossless Multiconductor Transmission Lines*, Harry Diamond Laboratories TR-1711 (June 1975).



(a) Cross-section geometry and terminations for a three-conductor transmission line.



(b) Axial parameters, x, l. Propagation velocity, v. Angle of EMP incidence ψ. Incident electric and magnetic fields E^e, H^e_Z. Poynting vector $\vec{P}$.

Figure 1. Physical and electrical transmission line parameters.

A = peak amplitude of the pulse in volts/meter.
M = normalization factor which makes the pulse reach amplitude, A, for all α_1 and α_2.
α_1 and α_2 are pulse-shaping constants.

The second of the exponential pulse forms is designated as Pulse(-1). This pulse is made up of several exponential terms, has a zero time derivative at time equal to zero, and can be made to have a zero cross-over at designated late times. Pulse(-1) is useful in representing EMP simulator fields such as those generated by AESOP (Army Electromagnetic Pulse Simulator Operations) and TEMPS (Transportable Electromagnetic Pulse Simulator) simulators at HDL.[3]

Pulse(-1). Time-domain expression for the electric field*

$$E_y^e(t) = (a-b)(1+gt)e^{-gt} + (b+d)(1+ht)e^{-ht} - a(1+mt)e^{-mt} - d(1+pt)e^{-pt} \quad (2)$$

where the pulse-shaping constants are given below with their corresponding FORTRAN variable equivalents in NLINE.

m = B1, h = B2, g = B3, p = B4, a = B5, b = B6, d = B7.

The basic waveshapes of Pulse(1) and Pulse(-1) are shown in figure 2.

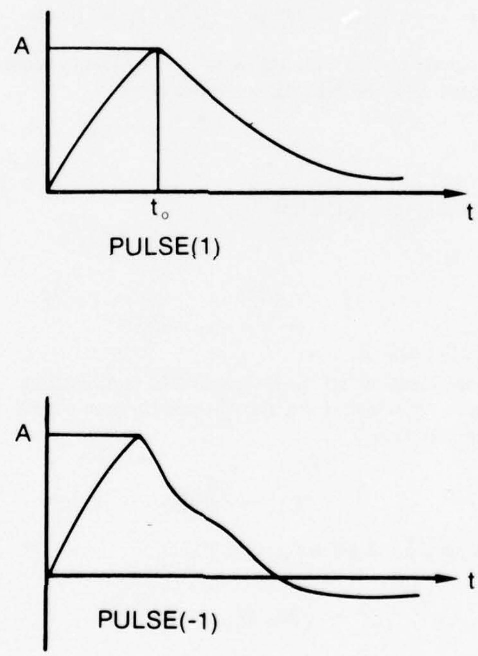


Figure 2. Basic pulse shapes of the input EMP to NLINE.

[3] E. Patrick, S. SooHoo, *Transportable Electromagnetic Pulse Simulator (TEMPS) Preliminary Field Mapping Report,* Harry Diamond Laboratories TM-74-15 (October 1974).

**After a pulse representation by R. F. Gray, HDL.*

3. OUTLINE OF EQUATIONS USED IN NLINE

NLINE is based on a solution for the TEM mode currents and voltages induced by the distributed external electromagnetic fields along the conductors. The equations governing the values of the current, *I*, and the voltage *V*, along the axial x-direction of the transmission line are given below.

$$\frac{d\underline{I}}{dx} + j\omega \underline{C}\,\underline{V} = \underline{H}^{e} \tag{3}$$

$$\frac{d\underline{V}}{dx} + j\omega \underline{L}\,\underline{I} = \underline{E}^{e} \tag{4}$$

where the underlined quantities denote matrix form. The matrices are of the order (n-1). Solutions for the voltages $\underline{V}$ and the currents $\underline{I}$ are derived in Frankel,[1] and are given in the form

$$\underline{I} = \underline{Y}\left(\underline{P}^{i}\cos\theta + j\underline{\mathrm{I}}\sin\theta\right)\underline{S}^{-1}\underline{K}(\ell) + \underline{W}(x) \tag{5}$$

$$\underline{V} = \left(\underline{\mathrm{I}}\cos\theta + j\underline{P}^{i}\sin\theta\right)\underline{S}^{-1}\underline{K}(\ell) + \underline{U}(x)\ . \tag{6}$$

The FORTRAN version of equations (5) and (6) is in the frequency domain and combined with the numerical Fourier transform, constitutes the NLINE computer code.

$\underline{\mathrm{I}}$ = the unit matrix order of (n-1).
n = number of conductors in the transmission line.
j = $\sqrt{-1}$
θ = kx
k = ω/v
ω = radian frequency in rad/s.
v = transmission-line propagation velocity.
$\underline{C}$ = Maxwell's capacitance coefficient matrix for the conductor cross section.
$\underline{L}$ = inductive coefficient matrix obtained from the $\underline{C}$ matrix, unit matrix $\underline{\mathrm{I}}$, and the line propagation velocity v by the following relation

$$\underline{L}\underline{C} = \frac{1}{v^2}\underline{\mathrm{I}} \tag{7}$$

The driving functions in equations (3) and (4) are given by

$$\underline{H}^{e} = \left(H_1, H_2, \ldots, H_{n-1}\right)^{T} \tag{8}$$

$$\underline{E}^{e} = \left(E_1, E_2, \ldots, E_{n-1}\right)^{T}.$$

[1] Sidney Frankel, *Cable and Multiconductor Transmission Line Analysis*, Harry Diamond Laboratories TR-091-1 (28 June 1974).

where T denotes transpose, converting $\underline{H}^e$ and $\underline{E}^e$ to column matrices. The i^{th} elements of equations (2), $i = 1,2,\ldots,(n-1)$ are defined by

$$H_i^e = j\omega C_i^e E_y(\omega) e^{j(\omega t - kx\cos\psi)}$$

$$E_i^e = j\omega L_i^e H_z(\omega) e^{j(\omega t - kx\cos\psi)} . \qquad (9)$$

Terms in equations (9) are outlined below.

t = time in seconds.

ψ = angle of EMP incidence shown in figure 1(b).

$E_y(\omega)$ = the resultant y-component of the external electric field, in volts/meter.

$H_z(\omega)$ = the resultant z-component of the external magnetic field, in amperes/meter.

The magnetic-field coupling parameter is defined in transpose form as follows:

$$\underline{L}^e = \left(L_1^e, L_1^e, \ldots, L_{n-1}^e\right)^T . \qquad (10)$$

$\underline{L}^e$ is an input parameter to NLINE, and is defined by Frankel[1] and Klebers.[2]

$$\underline{C}^e = \left(C_1^e, C_2^e, \ldots, C_{n-1}^e\right)^T \qquad (11)$$

C_i^e is computed in NLINE from

$$C_i^e = -\frac{1}{\mu}\sum_{j=1}^{n-1} L_j^e C_{ij} \qquad (12)$$

where μ is the permeability of free space.

The electric and magnetic fields are integrated over the parameter x in the following relations.

$$\underline{U}(x) = \int_o^x \left\{ \underline{E}^e(\xi)\cos[k(x-\xi)] - j\underline{Z}\underline{H}^e(\xi)\sin[k(x-\xi)] \right\} d\xi \qquad (13)$$

$$\underline{W}(x) = \underline{Y}\int_o^x \left\{ \underline{Z}\underline{H}^e(\xi)\cos[k(x-\xi)] - j\underline{E}^e(\xi)\sin[k(x-\xi)] \right\} d\xi \qquad (14)$$

where

$$\underline{Z} = v\,\underline{L} \qquad (15)$$

$$\underline{Y} = v\,\underline{C} .$$

[1] Sidney Frankel, *Cable and Multiconductor Transmission Line Analysis*, Harry Diamond Laboratories TR-091-1 (28 June 1974).

[2] Janis Klebers, *Electromagnetic Pulse Coupling with Lossless Multiconductor Transmission Lines*, Harry Diamond Laboratories TR-1711 (June 1975).

Other terms in equations (3) and (4) are

$$\underline{S} = \left(\underline{P}^{i} + \underline{P}^{o}\right)\cos k\ell + j\left(\underline{1} + \underline{P}^{o}\underline{P}^{i}\right)\sin k\ell \tag{16}$$

$$\underline{P}^{o} = \underline{ZY}^{o} \tag{17}$$

$$\underline{P}^{i} = \underline{ZY}^{i} \tag{18}$$

$$\underline{K}(\ell) = \underline{Z}\left[\underline{W}(\ell) - \underline{Y}^{o}\underline{U}(\ell)\right]. \tag{19}$$

The load impedances of the transmission line are introduced in the equations through admittance matrices $\underline{Y}^{i}$ and $\underline{Y}^{o}$, where the superscript "i" refers to loads at $x = 0$, and the superscript "o" refers to loads at $x = \ell$.

Elements of $\underline{Y}^{i}$ and $\underline{Y}^{o}$ are defined by

$$Y^{i}_{ij} = \begin{bmatrix} -\;Y^{L}_{ij}\,;\; i \neq j \\ \sum_{j=1}^{n-1} Y^{L}_{ij}\,;\; i = j \end{bmatrix} \tag{20}$$

$$Y^{o}_{ij} = \begin{bmatrix} -\;Y^{L}_{ij}\,;\; i \neq j \\ \sum_{j=1}^{n-1} Y^{L}_{ij}\,;\; i = j \end{bmatrix} \tag{21}$$

where Y^{L}_{ij} is the load admittance between the i^{th} and j^{th} conductors of the transmission line at the $x = 0$ end in equation (20), and at the $x = \ell$ end in equation (21), respectively.

In each case, the impedance between the i^{th} and j^{th} conductors is

$$Z^{L}_{ij} = \frac{1}{Y^{L}_{ij}}. \tag{22}$$

The Z^{L}_{ij} values are input parameters to NLINE.

4. DEFINITION OF NLINE INPUT PARAMETERS

The input parameters are defined and listed in sequence, as they are read from data cards in NLINE. The two-exponential Pulse(1) is read by data cards. The parameters for Pulse(-1) are changed within the NLINE deck. Setting the FORTRAN variable IMP = 1 in the NSD implies use of Pulse(1) for the computation. Setting IMP = - 1 implies use of Pulse(-1) for the computation.

The FORTRAN variables read by data cards into NLINE in the following order:

A = amplitude of the incident EMP in volts/meter.
A1 = α_1 in equation (1).
A2 = α_2 in equation (1).

The FORTRAN statements as they appear in NLINE for the above and subsequent variables are:

```
      READ(5,5000) A, A1, A2
5000  FORMAT(3E 10.0)
```

PERCEN = percent of free space propagation velocity observed in the transmission line.

```
      READ(5,5001)PERCEN
5001  FORMAT(F 5.0)
```

COMNT = user's comment (up to 80 characters)

```
      READ(5,505)(COMNT(MN),MN=1,8)
505   FORMAT(8A10)
```

MSETS = number of data sets where values for the transmission-line terminations, and/or angle of incidence, and/or line length may be parametrically changed, while holding reference conductor, cable cross section, and axial orientation with respect to the incident EMP constant.

NWIRES = total number of conductors in the transmission line. NLINE is dimensioned so that the limit for NWIRES is $1 \leq \text{NWIRES} \leq 11$.

```
      READ(5,500)MSETS,NWIRES
500   FORMAT(2I5)
```

CMAXWL = Maxwell's capacitance coefficients[4] for the transmission-line conductor configuration. A reduced matrix is used because the off-diagonal terms are symmetrical. These coefficients can be measured or computed by various methods. A program, PTNTL (Capacitance and Magnetic Field Coupling Code), is included in appendix A for one computation method.

The capacitance matrix is

$$(\text{CMAXWL}) = \begin{bmatrix} C_{11} & C_{12} & \cdots & C_{1n} \\ & C_{22} & \cdots & C_{2n} \\ \text{Symmetric terms not punched on data cards.} & & \ddots & \vdots \\ & & & C_{nn} \end{bmatrix}$$

For example $n = 3$ for a three-conductor transmission line. The CMAXWL array would be punched in the order given below:

$$\left(C_{11}, C_{12}, C_{13}, C_{22}, C_{23}, C_{33}\right)$$

where the symmetrical off-diagonal terms C_{21}, C_{31}, and C_{32} are not required. In general, for n conductors, $n(n+1)/2$ terms are read into the CMAXWL array.

```
      NCAPS=NWIRES*(NWIRES+1)/2
      READ(5,501)(CMAXWL(J),J+1,NCAPS)
501   FORMAT(8E10.0)
```

It is important to note that the CMAXWL array is converted to the full n by n-capacitance array in NLINE. However, the i^{th} row and i^{th} column are deleted from the array, after the i^{th} conductor has been designated as the reference conductor.

[4] S. Ramo and J. R. Whinnery, *Fields and Waves in Modern Radio*, John Wiley & Sons, Inc., New York (1964), 264-265.

For example: $n = 3$, the Maxwell's capacitance array generated from CMAXWL in NLINE is:

$$\underline{C} = \begin{bmatrix} C_{11} & C_{12} & C_{13} \\ C_{21} & C_{22} & C_{23} \\ C_{31} & C_{32} & C_{33} \end{bmatrix} . \tag{23}$$

For example, if conductor number three is chosen as the reference ($i = 3$), it is then redesignated as the 0^{th} conductor, and the reduced capacitance matrix used for the computations becomes

$$\underline{C}^{1} = \begin{bmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{bmatrix} . \tag{24}$$

Hence, the values for C_{13}, C_{23}, and C_{33} are not needed if the choice of reference conductor remains fixed for all computations.

ELI = the magnetic-field coupling parameter array, $\underline{L}^{e}$. The (NWIRES-1) terms are written into NLINE.

```
      READ(5,503)(ELI(J),J=1,(NWIRES-1)
503   FORMAT(8E10.0)
```

The magnetic-field coupling parameters can be measured, or computed.[1,2] The PTNTL program listed in appendix A performs this computation.

IQ = the integer number designating the chosen reference conductor.

```
      READ(5,504)IQ
504   FORMAT(I5)
```

ZI = $\underline{Z}^{L}$, the array of terminating impedances at the $x = 0$ end of the line.

ZO = $\underline{Z}^{L}$, the array of terminating impedances at the $x = \ell$ end of the line.

After IQ is chosen, the reference conductor is renumbered as zero (0), and the remaining conductors are renumbered consecutively 1 through $(n-1)$. The like subscripts, ii, designate impedance connected between the i^{th} conductor and the reference conductor (0). The subscripts, ij, designate impedances between the i^{th} and j^{th} conductors. The values for ZI and ZO are read row by row, left to right. For example: $n = 3$, the sequence of Z_{ij}^{L} stored in ZI is

$$\left(Z_{11}^{L}, Z_{12}^{L}, Z_{21}^{L}, Z_{22}^{L}\right) .$$

```
      N2=(NWIRES-1)**2
      READ(5,501)(ZI(J),J=1,N2)
      READ(5,501)(ZO(J),J=1,N2)
501   FORMAT(8E10.0)
```

PSI = ψ, the angle of incidence, in degrees, shown in figure 1(b).

TL = ℓ, line length, in meters.

```
      READ(5,502)PSI,TL
502   FORMAT(2F10.0)
```

[1] Sidney Frankel, *Cable and Multiconductor Transmission Line Analysis*, Harry Diamond Laboratories TR-091-1 (28 June 1974).

[2] Janis Klebers, *Electromagnetic Pulse Coupling with Lossless Multiconductor Transmission Lines*, Harry Diamond Laboratories TR-1711 (June 1975).

The remaining parameters under user control in NLINE are punched and changed within the deck itself. These parameters are listed below.

IMP = the parameter that determines which input EMP field is used. IMP=0 calls the unit impulse, IMP=1, calls Pulse(1), and IMP=-1 calls Pulse(-1).

B1, B2, B3, B4, B5, B6, and B7 are the Pulse(-1) parameters listed in equation (2).

IDATE = any integer number set by user as an identification number for the computation.

NXTIME = number of desired axial x-positions at which the computation is made.

X87 = fraction of the line length at which the NXTIME computations are to be made. For example, if computations are desired at $x = 0$, $x = 0.5\ell$, and $x = \ell$, holding all other line parameters constant, the user sets NXTIME=3 and X87(1)=0. , X87(2)=0.5, X87(3)=1.0.

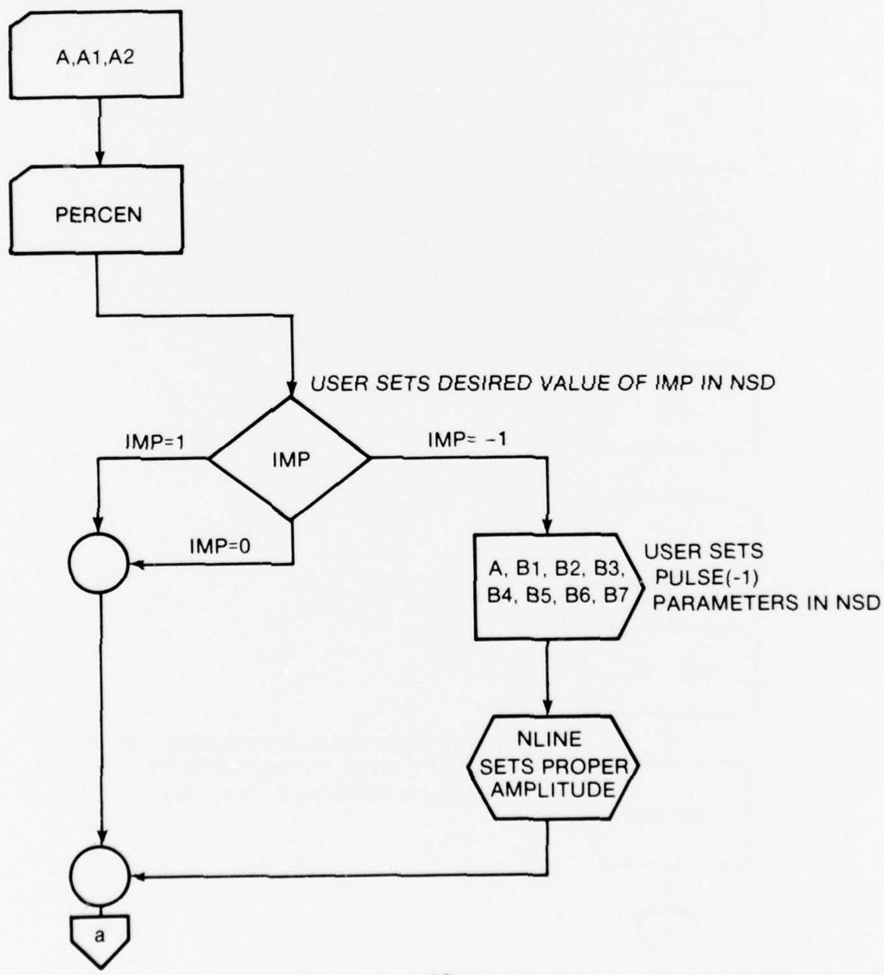
NCOUNT = number of frequency points at which the computations are made.

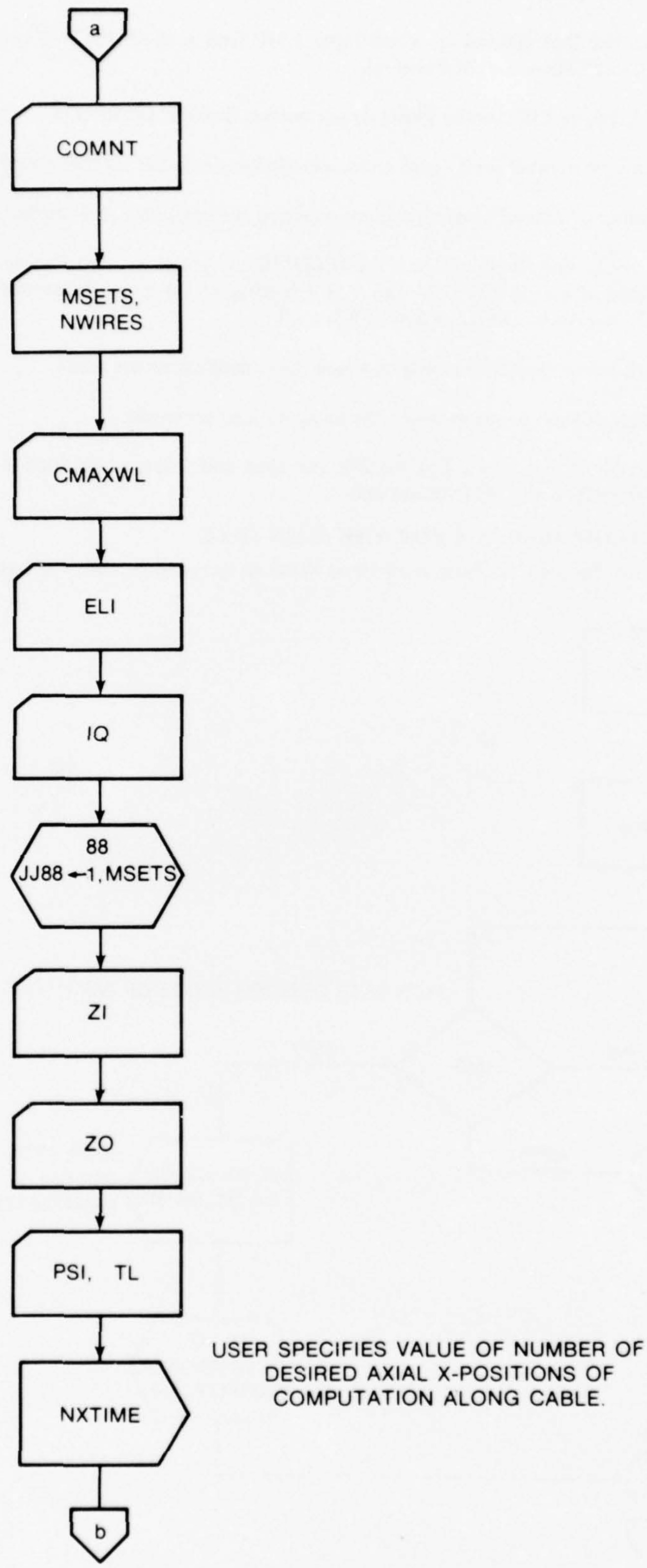
NTIME = number of time points at which the computations are made.

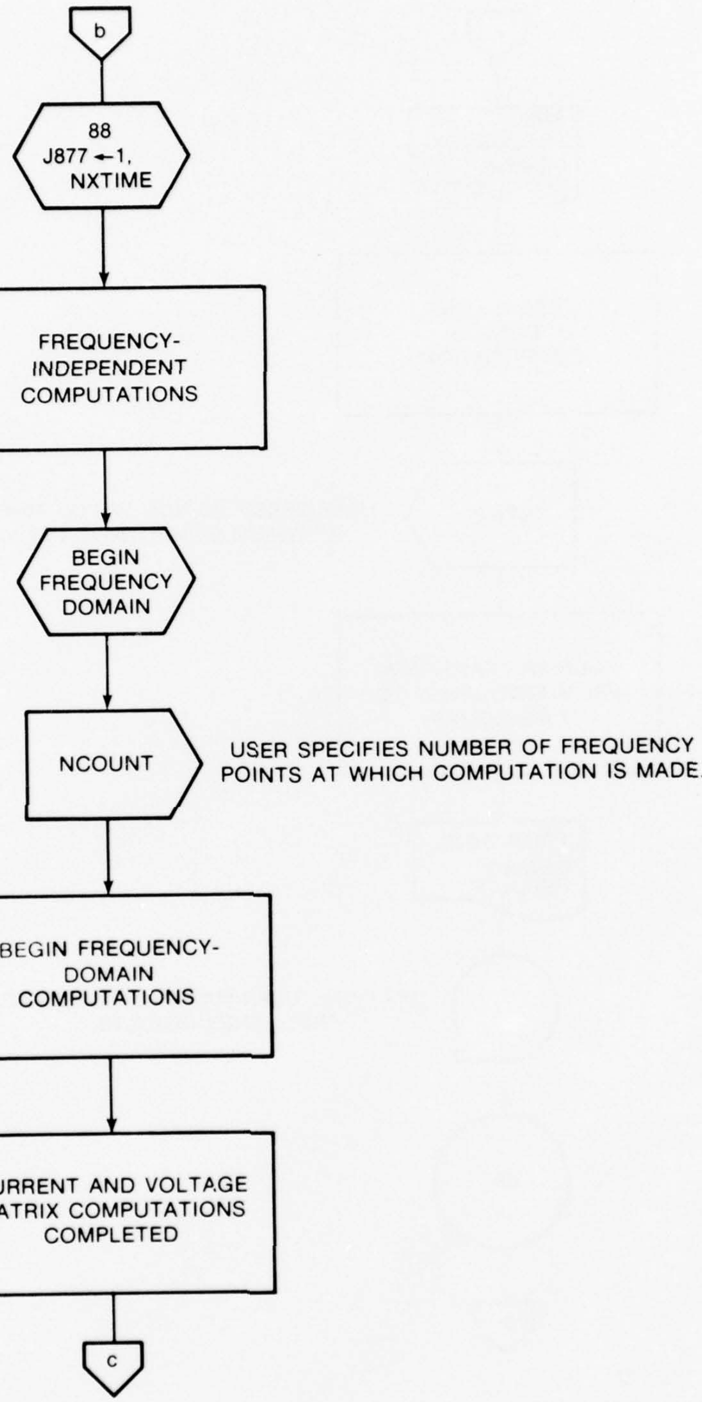
These parameters can be changed to adjust NLINE run time and Fourier transform accuracy. Maximum allowable values for NCOUNT and NTIME are 600.

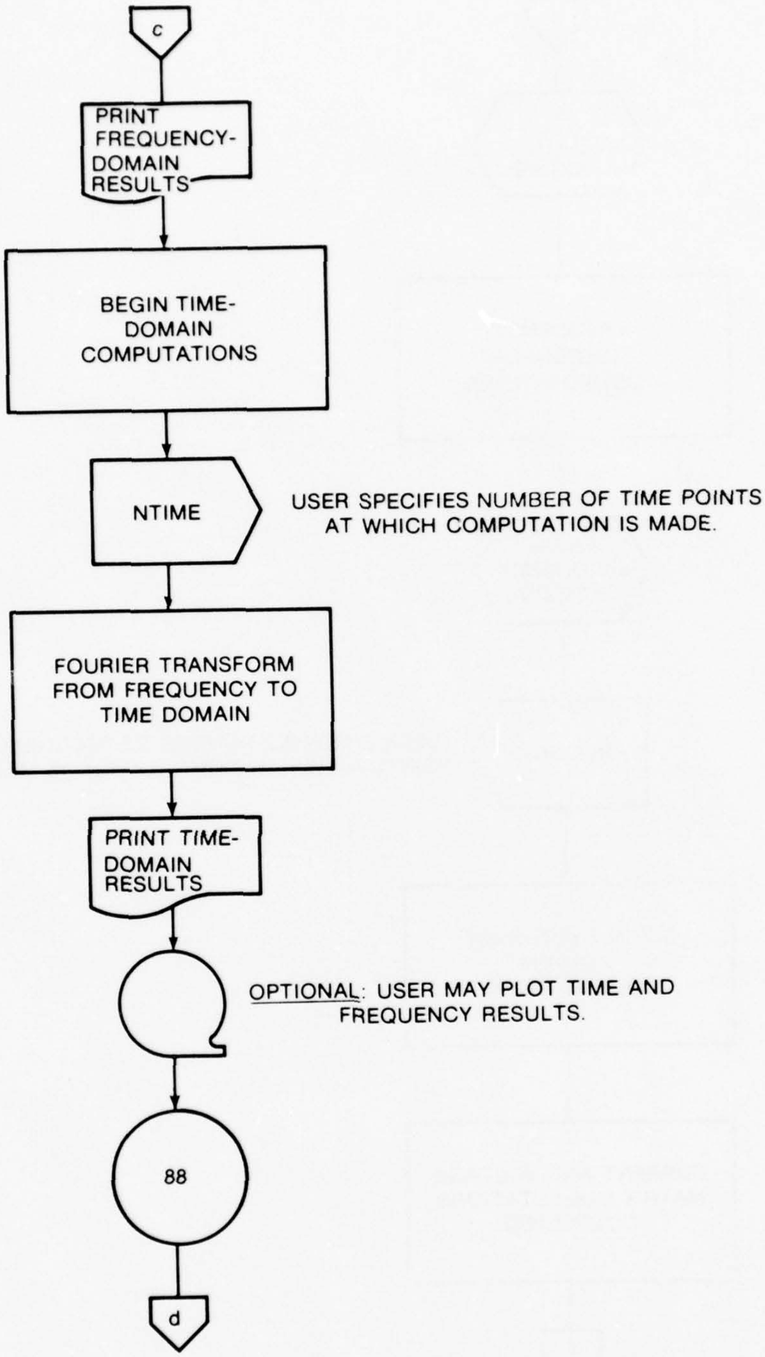
5. ABBREVIATED FLOW DIAGRAM FOR THE MAIN DECK

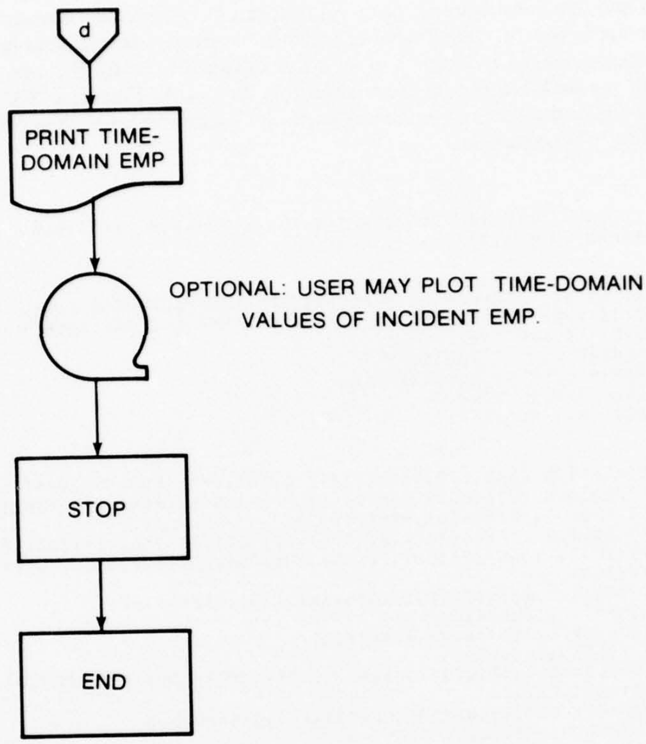
A flow diagram for the NLINE main program is listed in this section. Only the basic sequential events are included.




a
COMNT
MSETS,
NWIRES
CMAXWL
ELI
IQ
88
JJ88 ← 1, MSETS
ZI
ZO
PSI, TL
NXTIME
USER SPECIFIES VALUE OF NUMBER OF DESIRED AXIAL X-POSITIONS OF COMPUTATION ALONG CABLE.
b


b
88
J877 ← 1,
NXTIME
FREQUENCY-
INDEPENDENT
COMPUTATIONS
BEGIN
FREQUENCY
DOMAIN
NCOUNT
USER SPECIFIES NUMBER OF FREQUENCY POINTS AT WHICH COMPUTATION IS MADE.
BEGIN FREQUENCY-
DOMAIN
COMPUTATIONS
CURRENT AND VOLTAGE
MATRIX COMPUTATIONS
COMPLETED
c


c
PRINT FREQUENCY-DOMAIN RESULTS
BEGIN TIME-DOMAIN COMPUTATIONS
NTIME
USER SPECIFIES NUMBER OF TIME POINTS AT WHICH COMPUTATION IS MADE.
FOURIER TRANSFORM FROM FREQUENCY TO TIME DOMAIN
PRINT TIME-DOMAIN RESULTS
OPTIONAL: USER MAY PLOT TIME AND FREQUENCY RESULTS.
88
d


d
PRINT TIME-DOMAIN EMP
OPTIONAL: USER MAY PLOT TIME-DOMAIN VALUES OF INCIDENT EMP.
STOP
END

6. NLINE STANDARD DECK (NSD) LISTING

This section includes the listing for the entire NLINE computer program, including the main program and all subroutines and functions required for an NLINE run. A considerable amount of comment cards has been added for the user's benefit. Three types of comment cards have been placed in the deck. A plain "C" in the listing left margin designates location of an informative comment for the user. A "CR" in the margin locates a position in the deck where data are read in from data cards. Finally, a "CU" in the margin locates a point in the deck where the user can modify a particular parameter within the NLINE deck. This listing was tested on the CDC 6700 computer.

```
      PROGRAM NLINE(INPUT,OUTPUT,TAPE5=INPUT,RJK,TAPE2=RJK,
     1TAPE6=OUTPUT,TAPE1)
C
C
C     NLINE MULTICONDUCTOR TRANSMISSION LINE COMPUTER CODE. JUNE 1976.
C     THIS WORK WAS SPONSORED BY THE DEFENSE NUCLEAR AGENCY UNDER
C     SUBTASK R99QAXEB075.
C     DEPARTMENT OF THE ARMY
C     HARRY DIAMOND LABORATORIES
C     2800 POWDER MILL RD
C     ADELPHI, MD 20783
C
C
      DIMENSION CXMG(600,10),CXAT(600,10),VXMG(600,10),VXAT(600,10)
      DIMENSION E2TT(600),CSHC(600),FERK(600),FREK(600),TIME(600),
     1CTIM(600),VTIM(600),HZFTM(600)
      DIMENSION CMAXWL(100),ZI(100),ZC(100),YO(100),YI(100),PO(100),
     1PI(100),Y(100),C(100),Z(100),PP(100),SO(100),Q(100),CAP(100),
     2XP(100)
      DIMENSION X37(10),ELI(10),VXMAG(10),CXMAG(10)
      DIMENSION COMNT(8)
      COMPLEX E2TESS(600),TEMP(600)
      COMPLEX IIO(600)
      COMPLEX RC(100),CS(100),YOC(100),COMPZ(100),PVX(100),PIX(100),
     1VX(100),CX(100)
      COMPLEX UX(10),WX(10),UL(10),WL(10),XKL(10)
      COMPLEX ZUZ8,SJ,HZFREE
      COMMON/XYZ/KTCNT,NTH,TL,PSI,X
      COMMON/XEL/V,IMP
      COMMON/XSAV/CAP
      COMMON/FPAR/A1,A2,A
      COMMON/YODLL/B1,B2,B3,B4,B5,B6,B7
      DATA PIE,UM,RAD/3.1415927,1.25663706E-6,.01745329/
      CALL SYSTEMC(30,0,1,1,1,-1,-1)
      CALL SYSTEMC(115,0,1,1,1,-1,-1)
C
C     TWO EXPONENTIAL PULSE PARAMETERS ARE READ HERE.
C     REFER TO COMPLEX FUNCTION HZFREE.
CR
      READ(5,5000)A,A1,A2
 5000 FORMAT(3E10.0)
C
C     PERCEN=PERCENT FREE SPACE VELOCITY OF LINE
CR
      READ(5,5001)PERCEN
 5001 FORMAT(F5.0)
      V=PERCEN*3.E8
      SJ=CMPLX(0.,1.)
C
CU    USER SETS DESIRED VALUE OF (IMP) HERE.
C     IMP SPECIFIES TYPE OF INCIDENT PLANE WAVE PULSE SHAPE.
C     IMP=0, HZFREE=UNIT IMPULSE
C     IMP=-1,HZFREE=SPECIAL 4-EXPONENTIAL PULSE
C     IMP=+1,HZFREE=TWO EXPONENTIAL PULSE
C     THREE CARDS ARE INCLUDED HERE FOR THE THREE VALUES OF IMP.
C     PLACE DESIRED VALUE OF IMP LAST IN CARD SUCCESSION
C
      IMP=0
      IMP=1
      IMP=-1
```

```
      IF(IMP.EQ.-1)GO TO 1106
      GO TO 1107
 1106 CONTINUE
C
C     SAMPLE VALUES FOR THE 4-EXPONENTIAL PULSE PARAMETERS ARE GIVEN HERE.
C     REFER TO COMPLEX FUNCTION HZFREE.
C
      A=1.E2


      B1=7.E8
      B2=6.5E6
      B3=0.
      B4=0.
      B5=5.E4
      B6=5.E4
      B7=0.
      T=0.
      DTAU=5.E-10
      AMPTQ=0.
      DO 1105 NJQ3=1,300
      T=T+DTAU
      CALL TEMPLT(T,ETST,A,A1,A2,IMP)
      IF(ETST.GT.AMPTQ)AMPTQ=ETST
 1105 CONTINUE
      A=A*A/AMPTQ
 1107 CONTINUE
      IRUNO=0
C
CU    USER SETS DESIRED VALUE OF RUN IDENTIFICATION NUMBER HERE.
C     IDATE=RUN IDENTIFICATION NUMBER.
C     FOR EXAMPLE, DESIGNATE DATE OF RUN AS FOLLOWS.
C
      IDATE=04066
C
C     IDATE=IIJJK
C     II=DAY,JJ=MONTH,K=YEAR
C
      IDNTFN=IDATE*1000
      IDNTFN=IDNTFN+IRUNO
C
C     IDNTFN=I.D. NUMBER=IIJJKLLL,LLL=RUN NO.
C
C
C     USER GENERATED COMMENT OF FORTRAN CHARACTERS READ IN FROM
C     COLUMNS 1 THROUGH 80 ON DATA CARD.
CR
      READ(5,505)(COMNT(MN),MN=1,8)
  505 FORMAT(8A10)
      WRITE(6,602)(COMNT(MN),MN=1,8)
  602 FORMAT(1H1,8A10//)
C
C     MSETS=NUMBER OF DATA SETS WHERE VALUES FOR THE TRANSMISSION LINE
C           TERMINATIONS (ZI,ZO), AND/OR ANGLE OF EM WAVE INCIDENCE (PSI),
C           AND/OR TRANSMISSION LINE LENGTH (TL) MAY BE PARAMETRICALLY
C           CHANGED, WHILE HOLDING REFERENCE CONDUCTOR, CABLE CROSS SECTION,
C           AND AXIAL ORIENTATION WITH RESPECT TO INCIDENT EM FIELD CONSTANT.
C     NWIRES=NUMBER OF CABLE CONDUCTORS INCLUDING REFERENCE               06
CR
      READ(5,500)MSETS,NWIRES                                             05
  500 FORMAT(2I5)                                                         06
      NCAPS=NWIRES*(NWIRES+1)/2                                           06
      NP=NWIRES-1                                                         06
      N2=NP*NP                                                            06
C
C     MAXWELL CAPACITANCE COEFFICIENTS FOR THE
C     TRANSMISSION LINE ARE READ AT THIS POINT.
CR
      READ(5,501)(CMAXWL(J),J=1,NCAPS)                                    06
  501 FORMAT(8E10.0)                                                      06
C
C     MAGNETIC FIELD COUPLING PARAMETERS FOR THE
C     TRANSMISSION LINE ARE READ AT THIS POINT.
CR
      READ(5,503)(ELI(J),J=1,NP)                                          06
  503 FORMAT(8E10.0)                                                      06
```

```
C
C      IQ=REFERENCE CONDUCTOR NUMBER.  ONE OF THE (NWIRES) NUMBER OF CONDUCTORS
C      IN THE TRANSMISSION LINE IS CHOSEN AS THE REFERENCE.
CR
       READ(5,504)IQ                                                          07
  504 FORMAT(1I5)                                                             07
       DO 88 JJ88=1,MSETS
C
C      READ TERMINATION RESISTANCE VALUES AT X=0 END (ZI) AND X=TL END (ZO)
C      OF THE TRANSMISSION LINE.  TL=LENGTH OF THE TRANSMISSION LINE.
CR
       READ(5,501)(ZI(J),J=1,N2)
       READ(5,501)(ZO(J),J=1,N2)
       CALL RAR(ZI,2HZI,NP)
       CALL RAR(ZO,2HZO,NP)
C
C      ANGLE OF EMP INCIDENCE (PSI), AND TRANSMISSION LINE LENGTH (TL)
C      ARE READ HERE.
CR
       READ(5,502)PSI,TL
  502 FORMAT(2F10.0)
       CALL RVEC(ELI,2HLE,NP)
C
CU     USER SPECIFIES (NXTIME) AND X87(I),AS DEFINED BELOW, HERE.
C      NXTIME=NUMBER OF DESIRED AXIAL POSITIONS OF COMPUTATION
C      ALONG THE CABLE.
C      X87(I)=FRACTION OF TOTAL LENGTH OF CABLE AT WHICH
C      COMPUTATION IS MADE, I=1,2,...,NXTIME.
C      COMPUTATION IS MADE AT THE AXIAL POSITION, X=X87(I)*TL, WHERE
C      TL= LENGTH OF THE CABLE.
C
       NXTIME=1
       X87(1)=0.
       X87(2)=0.25
C
       DO 88 J877=1,NXTIME
       X=X87(J877)*TL
       CALL YOYI(YO,YI,ZO,ZI,NP)
       CALL RAR(YO,2HYO,NP)
       CALL RAR(YI,2HYI,NP)
       CALL POPI(NWIRES,IQ,YO,YI,PO,PI,Y,Z,CMAXWL)
       CALL RAR(PO,2HPO,NP)
       CALL RAR(PI,2HPI,NP)


C
C****BEGIN FREQUENCY DEPENDENT COMPUTATIONS.
C
CU     USER SPECIFIES (NCOUNT), AS DEFINED BELOW, HERE.
C      NCOUNT=NUMBER OF FREQUENCY POINTS.
C
       NCOUNT=600
C
C      OMEG1 FILLS THE ARRAY FREK WITH THE RADIAN FREQUENCY VALUES.
C       SEE SUBROUTINE OMEG1 FOR FREQUENCY GENERATION SCHEME.
C
       CALL OMEG1(FREK,NCOUNT)
       DO 87 LL8=1,NCOUNT
       W=FREK(LL8)
       BETA=W/V
       THETA=BETA*TL
       CC=COS(THETA)
       SN=SIN(THETA)
       CALL DADD(PO,PI,PP,N2)
       CALL SMLT(PP,CC,NP,PP)
       CALL SMLT(PO,SN,NP,SO)
       DO 56  JXX=1,N2
   56 XP(JXX)=PI(JXX)
       CALL MPRD(SO,XP,Q,NP,NP,0,0,NP)
       CALL XIDENT(NP,SO)
       DO 10 J=1,N2
   10 RC(J)=CMPLX(SO(J),0.)
       CALL SMLT(SO,SN,NP,SO)
       CALL DADD(SO,Q,Q,N2)
       DO 13 J=1,N2
```

```
C
C     CS=S MATRIX
C
   13 CS(J)=CMPLX(PP(J),Q(J))
      CALL CGELG(RC,CS,NP,NP,1.E-10,IER)
C
C     RC=S INVERSE MATRIX
C
      CALL UWOFX(X,W,Z,PSI,UX,WX,Y,NP,ELI)
      CALL UWOFX(TL,W,Z,PSI,UL,WL,Y,NP,ELI)
      DO 11 J=1,N2
      COMPZ(J)=CMPLX(Z(J),0.)
   11 YOC(J)=CMPLX(-YO(J),0.)
      CALL CMPRD(YOC,UL,CS,NP,NP,0,0,1)
      CALL CMADD(WL,CS,CS,NP)
      CALL CMPRD(COMPZ,CS,XKL,NP,NP,0,0,1)
C
C     XKL=K(L) VECTOR
C
      CALL FIN(X,BETA,PVX,PIX,Y,PI,NP)
      CALL CMPRD(RC,XKL,CS,NP,NP,0,0,1)
      DO 15 K=1,NP
   15 CX(K)=CS(K)
      CALL CMPRD(PVX,CS,XKL,NP,NP,0,0,1)
      CALL CMADD(XKL,UX,VX,NP)
      ZUZ8=CEXP(SJ*BETA*COS(PSI*RAD)*TL)
      CALL CSMLT(VX,ZUZ8,NP,VX)
C
C     VX=VOLTAGE VECTOR AT X
C
      CALL CMPRD(PIX,CX,XKL,NP,NP,0,0,1)
      CALL CMADD(XKL,WX,CX,NP)
      CALL CSMLT(CX,ZUZ8,NP,CX)
C
C     CX=CURRENT VECTOR AT X
C
      DO 14 J=1,NP
      CALL SMAG(CX(J),CXMG(LL8,J),CXAT(LL8,J))
   14 CALL SMAG(VX(J),VXMG(LL8,J),VXAT(LL8,J))
   87 CONTINUE
C
C****END FREQUENCY DEPENDENT COMPUTATIONS.

C     FREQUENCY DOMAIN RESULTS ARE PRINTED OUT BY SUBROUTINE (HEAD) AT EVERY
C     J-TH FREQUENCY VALUE.  J=1 PRINTS OUT ENTIRE FREQUENCY ARRAY OF RESULTS.
CU    USER SPECIFIES VALUE OF (J) HERE.
C
      J=30
      CALL HEAD(0,J,FREK,CXMG,CXAT,VXMG,VXAT,COMNT,TL,PSI,IQ,
     1NWIRES,IDNTFN,NP,NCOUNT,X)
C
C****BEGIN TIME DOMAIN COMPUTATIONS.
C     TIME ARRAY IS GENERATED HERE.
C     THE USER MAY WISH TO MODIFY FREQUENCY AND TIME
C     ARRAYS TO ACHIEVE MOST ACCURATE FOURIER TRANSFORM.
CU    USER SPECIFIES (NTIME), AS DEFINED BELOW, HERE.
C     NTIME=NUMBER OF TIME POINTS.
C
      NTIME=600
      TAU=TL/V
      DDTAU=100.
      DTAU=TAU/DDTAU
      TIME(1)=1.E-12
      ITIM8=1
      DO 1003 ITIM=2,50
      ITIM8=ITIM8+1
 1003 TIME(ITIM)=TIME(ITIM-1)+.1*DTAU
      NTMME=NTIME-ITIM8
      ITIM8=ITIM8+1
      DO 713 ITIM=ITIM8,NTMME
```

```
  713 TIME(ITIM)=TIME(ITIM-1)+DTAU
      NTIME =NTMME
      DO 89 NTH=1,NP
      DO 90 JJ=1,NCOUNT
   90 TEMP(JJ)=VXMG(JJ,NTH )*CEXP(SJ*VXAT(JJ,NTH )/57.2958)
C
C     FOURIER TRANSFORM FROM FREQUENCY TO TIME DOMAIN PERFORMED HERE.
C     USER MAY WISH TO SUBSTITUTE PERSONAL PREFERRED SUBROUTINE HERE.
C     SUBROUTINE TRANS IS USED HERE FOR THE FOURIER TRANSFORM.
C
      CALL TRANS(TEMP,VTIM,FREK,TIME,NCOUNT,NTIME,1.,0)
      DO 91 JJ=1,NCOUNT
   91 TEMP(JJ)=CXMG(JJ,NTH)*CEXP(SJ*CXAT(JJ,NTH)/57.2958)
C
C     SUBROUTINE TRANS IS USED HERE FOR THE FOURIER TRANSFORM.
C
      CALL TRANS(TEMP,CTIM,FREK,TIME,NCOUNT,NTIME,1.,0)
C
C     TIME DOMAIN RESULTS ARE PRINTED OUT BY SUBROUTINE (HTIM) AT EVERY J-TH
C     TIME VALUE.  J=1 PRINTS OUT ENTIRE TIME ARRAY OF RESULTS.
CU    USER SPECIFIES VALUE OF (J) HERE.
C
      J=20
      CALL HTTM(COMNT,IDNTFN,VTIM,CTIM,TIME,NTIME,J)
C
CU    USER MAY PLOT FREQUENCY AND TIME DOMAIN RESULTS FOR RESPONSE AT EACH
C     CONDUCTOR HERE.  USER MUST WRITE OWN PLOTTING INSTRUCTIONS COMPATIBLE
C     WITH LOCAL COMPUTER.
C
   89 CONTINUE
C
C**** END TIME DOMAIN COMPUTATIONS.
C
   88 CONTINUE
      DO 22211 LXJK=1,NCOUNT
22211 E2TESS(LXJK)=377.*HZFREE(FREK(LXJK),A,A1,A2,IMP)
      CALL TRANS(E2TESS,E2TT,FREK,TIME,NCOUNT,NTIME,1.,0)
C
C     TIME DOMAIN ELECTRIC FIELD USED AS THE
C     DRIVING SOURCE IS PRINTED AT THIS POINT.
C
      DO 22212 J=1,NTIME
22212 CALL TEMPLT(TIME(J),HZFTM(J),A,A1,A2,IMP)
      WRITE(6,700)IDNTFN,(COMNT(MN),MN=1,8),IDNTFN
  700 FORMAT(1H1,5HI.D.=,I9,10X8A10,10X5HI.D.=,I9//)
      WRITE(6,701)
  701 FORMAT(1H ,85HINCIDENT ELECTRIC FIELD FROM EXACT EQUATION AND FROM
     1 FOURIER TRANSFORM IN VOLTS/METER/)
      WRITE(6,702)
  702 FORMAT(1H ,4X9HTIME(SEC),7X5HEXACT,6X9HTRANSFORM)
      WRITE(6,703)(TIME(J),HZFTM(J),E2TT(J),J=1,NTIME,20)
  703 FORMAT(1P3E14.4)
      STOP
      END
```

```
      SUBROUTINE OMEG1(FREK,NCOUNT)
C     THIS SUBROUTINE GENERATES THE RADIAN FREQUENCY ARRAY.
      DIMENSION FREK(600)
      PIE=3.1415927
C     NPD=NUMBER OF FREQUENCY POINTS PER DECADE.
      NPD=120
      NDC=NCOUNT/NPD
C     D=LOWEST FREQUENCY VALUE.
      D=1.E5
      D=1.E7
      D=1.E4
      FR=0
      DW=D/FLOAT(NPD)*10.
      LL=0
      DO 2 J=1,NDC
      DO 3 L=1,NPD
      LL=LL+1
      FR=FR+DW
    3 FREK(LL)=FR
    2 DW=10.*DW
      RETURN
      END
```

```
      SUBROUTINE CVEC(VEC,LABL,NP)
C     CVEC PRINTS OUT THE COMPLEX VECTOR (VEC) NAMED (LABL)
      COMPLEX VEC(1)
      WRITE(6,9)LABL
    9 FORMAT(1H ,1A2)
      WRITE(6,10)(VEC(J),J=1,NP)
   10 FORMAT(10E11.3)
      RETURN
      END


      SUBROUTINE XIDENT(N,RI)
C     XIDENT GENERATES AN N BY N UNIT MATRIX.
C     CALLED FROM FIN,POPI
      DIMENSION RI(1)
      L=0
      DO 10J=1,N
      DO 10K=1,N
      L=L+1
      IF(J.EQ.K)GO TO 12
      RI(L)=0.
      GO TO 10
   12 RI(L)=1.
   10 CONTINUE
      RETURN
      END

      SUBROUTINE MPRD(A,B,R,NRA,NCARB,L,N,NCB)
C     MPRD PERFORMS THE MATRIX PRODUCT (A)*(B), AND
C     RETURNS RESULTING MATRIX INTO (R).
C     CALLED FROM UWDFX,POPI
      DIMENSION A(1),B(1),R(1)
      LN=N*L
      DO 10 I=1,NRA
      DO 10 J=1,NCB
      Q=0.
      DO 10 K=1,NCARB
      IKA=(I-1)*NCARB+K
      KJB=(K-1)*NCB+J
      IJR=(I-1)*NCB+J
      Q=Q+A(IKA)*B(KJB)
   10 R(IJR)=Q
      RETURN
      END


      SUBROUTINE CAR(AR,LABL,NP)
C     CAR PRINTS OUT THE COMPLEX MATRIX (AR) NAMED (LABL)
      COMPLEX AR(1)
      N2=NP*NP
      WRITE(6,7)LABL
    7 FORMAT(1H ,1A2)
      WRITE(6,8)(AR(J),J=1,N2)
    8 FORMAT(10E11.3)
      RETURN
      END


      SUBROUTINECMPRD(A,B,R,NRA,NCARB,L,N,NCB)
C     CMPRD PERFORMS MULTIPLICATION OF TWO
C     COMPLEX MATRICES (R)=(A)*(B).
C     CALLED FROM FIN,UWDFX,NLINE
      COMPLEX A(1),B(1),R(1),Q
      LN=N*L
      DO 10 I=1,NRA
      DO 10 J=1,NCB
      Q=CMPLX(0.,0.)
      DO 10 K=1,NCARB
      IKA=(I-1)*NCARB+K
      KJB=(K-1)*NCB+J
      IJR=(I-1)*NCB+J
      Q=Q+A(IKA)*B(KJB)
   10 R(IJR)=Q
      RETURN
      END
      SUBROUTINE DADD(A,B,C,N)
C     DADD ADDS THE MATRIX (B) TO MATRIX (A).
C     CALLED FROM NLINE
      DIMENSION A(1),B(1),C(1)
      DO 2 J=1,N
    2 C(J)=A(J)+B(J)
      RETURN
      END

      SUBROUTINE RVEC(VEC,LABL,NP)
C     RVEC PRINTS OUT THE VECTOR (VEC) NAMED (LABL)
C     CALLED FROM NLINE
      DIMENSION VEC(1)
      WRITE(6,7)LABL
    7 FORMAT(1H ,1A2)
      WRITE(6,6)(VEC(J),J=1,NP)
    6 FORMAT(1H ,10E11.3)
      RETURN
      END
```

```
      SUBROUTINE FIELDS(PSI,DXL,HZCOS,HZSIN,EYCOS,EYSIN,W)
C     THIS SUBROUTINE PERFORMS INTERMEDIATE CALCULATIONS.
C     CALLED FROM UWDFX
      COMPLEX HZCOS,HZSIN,EYCOS,EYSIN,SJ,EJK,EJM,HOW,EH,HZFREE
      COMMON/XEL/V,IMP
      COMMON/FPAR/A1,A2,A
      DATA Z/377./
      DXL2=DXL/2.
      SJ=CMPLX(0.,1.)
      XK=W/V
      RPSI=PSI/57.29578
      CPSI=COS(RPSI)
      PK=XK*CPSI
      PP=XK+PK
      PM=XK-PK
      SP=SIN(PP*DXL2)
      SM=SIN(PM*DXL2)
      EJK=CEXP(-SJ*XK*DXL2)*SP/PP
      IF(PM.EQ.0.)GOTO 11
      EJM=CEXP(SJ*XK*DXL2)*SM/PM
      GO TO 12
   11 EJM=CEXP(SJ*XK*DXL2)
   12 HOW=HZFREE(W,A,A1,A2,IMP)
      EH=HOW*CEXP(-SJ*PK*DXL2)
      HZCOS=EH*(EJM+EJK)
      HZSIN=-SJ*EH*(EJM-EJK)
      EYCOS=HZCOS*Z*CPSI
      EYSIN=HZSIN*Z*CPSI
      RETURN
      END


      SUBROUTINE RAR(AR,LABL,NP)
C     RAR PRINTS OUT THE MATRIX (AR) NAMED (LABL)
C     CALLED FROM POPI,NLINE
      DIMENSION AR(1)
      N2=NP*NP
      WRITE(6,7)LABL
    7 FORMAT(1H ,1A2)
      WRITE(6,8)(AR(J),J=1,N2)
    8 FORMAT(10E11.3)
      RETURN
      END

      SUBROUTINE TEMPLT(T,E,A,A1,A2,IMP)
      COMMON/YODLL/B1,B2,B3,B4,B5,B6,B7
      IF (IMP)2,3,4
    3 E=1.
      RETURN
    4 TT=ALOG(A2/A1)/(A2-A1)
      TM=EXP(-A1*TT)-EXP(-A2*TT)
      AM=A/TM
      E=AM*(EXP(-A1*T)-EXP(-A2*T))
      RETURN
    2 CONTINUE
      B8=(B5-B6)*(1.+B3*T)*EXP(-B3*T)
      B9=(B6+B7)*(1.+B2*T)*EXP(-B2*T)
      B10=-B5*(1.+B1*T)*EXP(-B1*T)
      B11=-B7*(1.+B4*T)*EXP(-B4*T)
      E=A*(B8+B9+B10+B11)
      RETURN
      END

      SUBROUTINE CMADD(A,B,C,N)
C     CMADD ADDS TWO N BY N COMPLEX MATRICES (A) AND (B).
C     CALLED FROM FIN,UWDFX,NLINE
      COMPLEX A(1),E(1),C(1)
      DO 2 J=1,N
    2 C(J)=A(J)+B(J)
      RETURN
      END

      SUBROUTINE SMLT(RIN,V,N,ROUT)
C     SMLT MULTIPLIES THE MATRIX (RIN) BY THE CONSTANT (V).
C     CALLED FROM FIN,POPI,NLINE
      DIMENSION RIN(1),ROUT(1)
      NN=N*N
      DO 10 J=1,NN
   10 ROUT(J)=V*RIN(J)
      RETURN
      END

      SUBROUTINE GELG(R,A,M,N,EPS,IER)
C     GELG PERFORMS MATRIX INVERSION FOR REAL MATRICES.
C     CALLED FROM POPI
C     TAKEN FROM IBM SYSTEM/360 SCIENTIFIC SUBROUTINE PACKAGE, 1967,
C     REPORT NO. H20-0166-4, PAGES 179-181.
      DIMENSION A(1),R(1)
      DATA ZERO/0.000/,HALF/0.500/,ONE/1.000/
      IF(M)23,23,1
1     IER=0
      PIV=ZERO
      MM=M*M
      NM=N*M
      DO 3 L=1,MM
      TB=A(L)
      IF(TB.LT.ZERO) TB=-TB
      IF(TB-PIV)3,3,2
```

```
2       PIV=TB
        I=L
3       CONTINUE
        TOL=EPS*PIV
        LST*1
        DO 17 K=1,M
        IF(PIV) 23,23,4
4       IF(IER)7,5,7
5       IF(PIV-TOL)6,6,7
6       IER=K-1
7       PIVI=ONE/A(I)
        J=(I-1)/M
        I=I-J*M-K
        J=J+1-K
        DO 8 L=K,NM,M
        LL=L+I
        TB=PIVI*R(LL)
        R(LL)=R(L)
8       R(L)=TB
        IF(K-M)9,18,18
9       LEND=LST+M-K
        IF(J) 12,12,10
10      II=J*M
        DO 11 L=LST,LEND
        TB=A(L)
        LL=L+II
        A(L;=A(LL)
11      A(LL)=TB
12      DO 13 L=LST,MM,M
        LL=L+I
        TB=PIVI*A(LL)
        A(LL)=A(L)
13      A(L)=TB
        A(LST)=J

        PIV=ZERJ
        LST=LST+1
        J=0
        DO 16 II=LST,LEND
        PIVI=-A(II)
        IST=II+M
        J=J+1
        DO 15 L=IST,MM,M
        LL=L-J
        A(L)=A(L)+PIVI*A(LL)
        TB=A(L)
        IF(TB.LT.ZERO) TB=-TB
        IF(TB-PIV)15,15,14
14      PIV=TB
        I=L
15      CONTINUE
        DO 16 L=K,NM,M
        LL=L+J
16      R(LL)=R(LL)+PIVI*R(L)
17      LST=LST+M
18      IF(M-1) 23,22,19
19      IST=MM+M
        LST=M+1
        DO 21 I=2,M
        II=LST-I
        IST=IST-LST
        L=IST-M
        L=A(L)+HALF
        DO 21 J=II,NM,M
        TB=R(J)
        LL=J
        DO 20 K=IST,MM,M
        LL=LL+1
20      TB=TB-A(K)*R(LL)
        K=J+L
        R(J)=R(K)
21      R(K)=TB
22      RETJRN
23      IER=-1
        RETURN
        END
        SUBROUTINECGELG(R,A,M,N,EPS,IER)
C       CGELG PERFORMS COMPLEX MATRIX INVERSION.
C       CALLED FROM NLINE
C
C
          CJMPLEX R(1),A(1),PIVI,CTB
        IF(M)23,23,1
C
C       SEARCH FOR GREATEST ELEMENT IN MATRIX A
      1 IER=0
        PIV=0.
        MM=M*M
        NM=N*M
```

```
      DO 3 L=1,MM
      TB=CABS(A(L))
      IF(TB-PIV)3,3,2
    2 PIV=TB
      I=L
    3 CONTINUE
C     A(I) IS PIVOT ELEMENT. PIV CONTAINS THE ABSOLUTE VALUE OF A(I).
      TOL=EPS*PIV
C
C
C     START ELIMINATION LOOP
      LST=1
      DO 17 K=1,M
C
C     TEST ON SINGULARITY
      IF(PIV)23,23,4
    4 IF(IER)7,5,7
    5 IF(PIV-TOL)6,6,7
    6 IER=K-1
    7 PIVI=1./A(I)
      J=(I-1)/M
      I=I-J*M-K
      J=J+1-K
C     I+K IS ROW-INDEX. J+K COLUMN-INDEX OF PIVOT ELEMENT
C
C     PIVOT ROW REDUCTION AND ROW INTERCHANGE IN RIGHT HAND SIDE R
      DO 3 L=K,NM,M
      LL=L+I
      CTB=PIVI*R(LL)
      R(LL)=R(L)
    8 R(L)=CTB
C
C     IS ELIMINATION TERMINATED
      IF(K-M)9,18,18
C
C     COLUMN INTERCHANGE IN MATRIX A
    9 LEND=LST+M-K
      IF(J)12,12,10
   10 II=J*M
      DO 11 L=LST,LEND
      CTB=A(L)
      LL=L+II
      A(L)=A(LL)
   11 A(LL)=CTB
C
C     ROW INTERCHANGE AND PIVOT ROW REDUCTION IN MATRIX A
   12 DO 13 L=LST,MM,M
      LL=L+I
      CTB=PIVI*A(LL)
      A(LL)=A(L)
   13 A(L)=CTB
C
C     SAVE COLUMN INTERCHANGE INFORMATION
      X=REAL(A(LST))
      X=J
      A(LST)=CMPLX(X,0.)
C
C     ELEMENT REDUCTION AND NEXT PIVOT SEARCH
      PIV=0.
      LST=LST+1
      J=0
      DO 16 II=LST,LEND
      PIVI=-A(II)
      IST=II+M
      J=J+1
      DO 15 L=IST,MM,M
      LL=L-J
      A(L)=A(L)+PIVI*A(LL)
      TB=CABS(A(L))
      IF(TB-PIV)15,15,14
   14 PIV=TB
      I=L
   15 CONTINUE
      DO 16 L=K,NM,M
      LL=L+J
```

```
   16 R(LL)=R(LL)+PIVI*R(L)
   17 LST=LST+M
C     END OF ELIMINATION LOOP
C
C
C     BACK SUBSTITUTION AND BACK INTERCHANGE
   18 IF(M-1)23,22,19
   19 IST=MM+M
      LST=M+1
      DO 21 I=2,M
      II=LST-I
      IST=IST-LST
      L=IST-M
      L=REAL(A(L))+.5
      DO 21 J=II,MM,M
      CTB=R(J)
      LL=J
      DO 20 K=IST,MM,M
      LL=LL+1
   20 CTB=CTB-A(K)*R(LL)
      K=J+L
      R(J)=R(K)
   21 R(K)=CTB
   22 RETURN
C
C
C     ERROR RETURN
   23 IER=-1
      RETURN
      END


      COMPLEX FUNCTION HZFREE(W,A,A1,A2,IMP)
      COMPLEX B8,B9,B10,B11
C     HZFREE=COMPLEX AMPLITUDE OF INCIDENT MAGNETIC FREE FIELD
C     IN THE TRANSVERSE PLANE OF THE NLINE AS A FUNCTION OF W(RAD/SEC).
C     CALLED FROM FIELDS
C     A=PEAK TIME DOMAIN ELECTRIC FREE FIELD AMPLITUDE IN VOLTS/METER
C     A1,A2=TWO EXPONENTIAL PULSE SHAPE PARAMETERS
C     IMP SPECIFIES TYPE OF MAGNETIC FIELD INPUT PULSE SHAPE
C     IMP=0, HZFREE=UNIT IMPULSE
C     IMP=+1,HZFREE=TWO EXPONENTIAL PULSE
C     IMP=-1,HZFREE=SPECIAL 4-EXPONENTIAL PULSE
      COMMON/YODLL/B1,B2,B3,B4,B5,B6,B7
      TO =ALOG(A2/A1)/(A2-A1)
      TM=EXP(-A1*TO)-EXP(-A2*TO)
      XA=A/TM/377.
      IF(IMP)5,2,3
    2 HZFREE=CMPLX(1.,0.)
      GO TO 4
    3 HZFREE=XA*(1./CMPLX(A1,W)-1./CMPLX(A2,W))
      GO TO 4
    5 XA=A/377.
      B8=(B7+B6)*(1.+B2/CMPLX(B2,W))/CMPLX(B2,W)
      B9=-B5*(1.+B1/CMPLX(B1,W))/CMPLX(B1,W)
      B10=(B5-B6)*(1.+B3/CMPLX(B3,W))/CMPLX(B3,W)
      B11=-B7*(1.+B4/CMPLX(B4,W))/CMPLX(B4,W)
      HZFREE=XA*(B8+B9+B10+B11)
    4 CONTINUE
      RETURN
      END
      SUBROUTINE HEAD(I,J,FREK,CXMG,CXAT,VXMG,VXAT,COMNT,TL,PSI,IQ,
     1NWIRES,IDNTFN,NP,NCOUNT,X)
C     HEAD PRINTS OUT THE FREQUENCY DOMAIN RESULTS.
C     CALLED FROM NLINE
      DIMENSION FREK(600),CXMG(600,10),CXAT(600,10),VXMG(600,10),
     1VXAT(600,10),COMNT(8)
C
C     I=0, PRINT VX...I=1,PRINT IX
C     J=PRINT EVERY J-TH VALUE.(J=1 PRINTS ALL FREK VALUES)
C
      IDNTFN=IDNTFN+1
      XX=X/TL
      WRITE(6,600)IDNTFN,(COMNT(MN),MN=1,8),IDNTFN
```

```
600 FORMAT(1H1,5HI.D.=,I9,10X8A10,10X5HI.D.=,I9//)
    IF(I)2,3,2
  3 WRITE(6,601)XX,TL,PSI
601 FORMAT(1H ,14HVOLTAGES AT X=,1F4.2,12H*LINE LENGTH,3X2HL=,
   11E14.4,3X4HPSI=,1F6.2//)
604 FORMAT(1H ,14HCURRENTS AT X=,1F4.2,12H*LINE LENGTH,3X2HL=,
   11E14.4,3X4HPSI=,1F6.2//)
    WRITE(6,605)
605 FORMAT(1H ,2X7HRAD/SEC,1X11HCONDUCTOR 1,7X1H2,10X1H3,10X1H4,10X1H5
   1,10X1H6,10X1H7,10X1H8,10X1H9,9X2H10/)
    DO 10 K=1,NCOUNT,J
    WRITE(6,602)FREK(K),(VXMG(K,M),M=1,NP)
 10 WRITE(6,603)(VXAT(K,M),M=1,NP)
602 FORMAT(1H ,1E10.2,11E11.3)
603 FORMAT(1H ,6X3HARG,1X11E11.3)
    GO TO 4
  2 WRITE(6,604)XX,TL,PSI
    WRITE(6,605)
    DO 11 K=1,NCOUNT,J
    WRITE(6,602)FREK(K),(CXMG(K,M),M=1,NP)
 11 WRITE(6,603)(CXAT(K,M),M=1,NP)
  4 RETURN
    END

      SUBROUTINE CSMLT(RIN,V,N,ROUT)
C     CALLED FROM FIN,UWOFX,NLINE
      COMPLEX RIN(1),ROUT(1),V
C     MATRIX OR VECTOR RIN(J) MULTIPLIED BY A COMPLEX CONSTANT, V.
      DO 10 J=1,N
   10 ROUT(J)=V*RIN(J)
      RETURN
      END

      SUBROUTINE FIN(X,BETA,PVX,PIX,Y,PI,NP)
C     THIS SUBROUTINE PERFORMS INTERMEDIATE CALCULATIONS.
C     CALLED FROM NLINE
      DIMENSION PI(100),XI(100),P8(100),Y(100)
      COMPLEX PVX(1),PIX(1),SJ,S,CC,XC(100),XX(100),PP(100),P9(100)
      SJ=CMPLX(0.,1.)
      N2=NP*NP
      CALL XIDENT(NP,XI)
      DO 10 J=1,N2
      P9(J)=CMPLX(PI(J),0.)
   10 XX(J)=CMPLX(XI(J),0.)
      THETA=BETA*X
      C=COS(THETA)
      S=SIN(THETA)*SJ
      CALL CSMLT(P9,S,N2,PVX)
      CC=CMPLX(C,0.)
      CALL CSMLT(XX,CC,N2,XC)
      CALL CMADD(XC,PVX,PVX,N2)
      CALL SMLT(PI,C,NP,P8)
      CALL CSMLT(XX,S,N2,XC)
      DO 11 J=1,N2
   11 PP(J)=CMPLX(P8(J),0.)
      CALL CMADD(PP,XC,XC,N2)
      CALL SMLT(Y,-1.,NP,XI)
      DO 12 J=1,N2
   12 XX(J)=CMPLX(XI(J),0.)
       CALL CMPRD(XX,XC,PIX,NP,NP,0,0,NP)
      RETURN
      END
      SUBROUTINE SMAG(A,B,AGMT)
C     SMAG CONVERTS THE COMPLEX NUMBER (A) TO POLAR FORM.  B=MAGNITUDE OF (A)
C     AND (AGMT) IS THE ARGUMENT OF (A).
C     CALLED FROM NLINE
      COMPLEX A,C
      C=CONJG(A)
      C=A*C
    2 B=SQRT(REAL(C))
      AR=REAL(A)
      AI=AIMAG(A)
      IF(AR)3,4,3
    4 IF(AI)5,6,7
```

```
    6 AGMT=0.
      GO TO 8
    5 AGMT=270.
      GO TO 8
    7 AGMT=90.
      GOTO 8
    3 AGMT=57.29578*ATAN2(AI,AR)
      IF(AGMT)9,8,8
    9 AGMT=AGMT+360.
    8 RETJRN
      END
      SUBROUTINE DELETX(I,N,A,B)
C     CALLED FROM POPI
C     DELETES I-TH COLUMN AND ROW OF N*N MATRIX A, ANDRETURNS N1*N1  B.
      DIMENSION A(1),B(1)
      N1=N-1
      L=0
      DO 10 J=1,N
      DO 10 K=1,N
      IF(J.EQ.I)GOTO 10
      IF(K.EQ.I)GOTO 10
      L=L+1
      B(L)=A(N*(J-1)+K)
   10 CONTINUE
      RETJRN
      END


      SUBROUTINE JWOFX(X,W,Z,PSI,UX,WX,Y,N,ELJ)
C     CALLED FROM NLINE
      DIMENSION Z(1),ELJ(10),CAP(100),ECI(10),Y(1),EC2(10),Q(100)
      COMPLEX UX(1),WX(1),SJ,HZCOS,HZSIN,EYCOS,CELJ(10),ELJC(10),
     1YY(100),ECIC(10),EC2C(10),W8(10),E8(10),EYSIN
      COMMON/XSAV/CAP
      U=1.25663706E-6
      SJ=CMPLX(0.,1.)
      N2=N*N
      CALL FIELDS(PSI,X,HZCOS,HZSIN,EYCOS,EYSIN,W)
      HZCOS=HZCOS*SJ*W
      HZSIN=HZSIN*W
      EYCOS=EYCOS*SJ*W
      EYSIN=EYSIN*W
      DO 14 I=1,N
      C=0.
      DO 9 J=1,N
      NQ=N*(I-1)+J
    9 C=C+ELJ(J)*CAP(NQ)
   14 ECI(I)=-C/U
      DO 10 J=1,N
   10 ELJC(J)=CMPLX(ELJ(J),0.)
      CALL CSMLT(ELJC,HZCOS,N,CELJ)
      DO 13 JQ=1,N2
   13 Q(JQ)=Z(JQ)
      CALL MPRD(Q,ECI,EC2,N,N,0,0,1)
      DO 12 K=1,N
   12 EC2C(K)=CMPLX(EC2(K),0.)
      CALLCSMLT(EC2C,EYSIN,N,E8)
      CALL CMADD(CELJ,E8,UX,N)
      CALL CSMLT(ELJC,HZSIN,N,ELJC)
      CALL CSMLT(EC2C,EYCOS,N,ECIC)
      CALL CMADD(ECIC,ELJC,W8,N)
      DO 11 J=1,N2
   11 YY(J)=CMPLX(Y(J),0.)
      CALL CMPRD(YY,W8,WX,N,N,0,0,1)
      RETJRN
      END
      SUBROUTINE POPI(NWIRES,IQ,YO,YI,PO,PI,Y,Z,C)
C     THIS SUBROUTINE PERFORMS INTERMEDIATE CALCULATIONS.
C     CALLED FROM NLINE
      DIMENSION PO(1),PI(1),YO(1),YI(1),Y(1),Z(1),C(1),RI(100),CAP(100)
     1,CC(100),COP(100)
      COMMON/XEL/V,IMP
      COMMON/XSAV/CAP
      DATA EP/1.E-10/
      NP=NWIRES-1
      N2=NP*NP
      L=0
```

```
      DO 10 I=1,NWIRES
      DO 10 J=I,NWIRES
      L=L+1
      NQ=NWIRES*(I-1)+J
      NR=NWIRES*(J-1)+I
      CC(NQ)=C(L)
   10 CC(NR)=CC(NQ)
C     CC=EXPANDED CAPACITANCE MATRIX
      CALL RAR(CC,2HCC,NWIRES)
      CALL XIDENT(NP,RI)
      CALL DELETX(IQ,NWIRES,CC,CAP)
C     CAP=REDUCED CAPACITANCE MATRIX
      CALL RAR(CAP,2HC ,NP)
      CALL SMLT(CAP,V,NP,Y)
C     Y=Y MATRIX
      DO 30 KM=1,N2
   30 COP(KM)=CAP(KM)
      CALL GELG(RI,COP,NP,NP,EP,IER)
C     RI=CAP INVERSE
      IF(IER.NE.0)GOTO 16
      GO TO 17
   16 WRITE(6,601)I,IER
  601 FORMAT(1H ,48HUNSUCCESSFUL INVERSION OF CAPACITANCE MATRIX**N=,1I
     13,3X4HIER=,1I3////)
   17 Q=1./V
      CALL SMLT(RI,Q,NP,Z)
C     Z=Z MATRIX
      CALL RAR(RI,2HC-,NP)
      CALL RAR(Y,2HY ,NP)
      CALL RAR(Z,2HZ ,NP)
      CALL MPRD(Z,YI,PI,NP,NP,0,0,NP)
      CALL MPRD(Z,YO,PO,NP,NP,0,0,NP)
      RETURN
      END



      SUBROUTINE HTTM(COMNT,IDNTFN,VT,CT,T,NTIME,N)
C     HTIM WRITES TIME DOMAIN HEADINGS IN THE PRINTOUT.
C     CALLED FROM NLINE
      DIMENSION VT(1),CT(1),T(1)
      DIMENSION COMNT(8)
      COMMON/XYZ/KTCNT,NTH,TL,PSI,X
      COMMON/XEL/V,IMP
      TAU=TL/V
      IDNTFN=IDNTFN+1
      XX=X/TL
      WRITE(6,600)IDNTFN,(COMNT(MN),MN=1,8),IDNTFN
  600 FORMAT(1H1,5HI.D.=,I9,10X8A10,10X5HI.D.=,I9//)
      WRITE(6,601)XX,TL,PSI
  601 FORMAT(1H ,14HRESPONSE AT X=,1F4.2,12H*LINE LENGTH,3X2HL=,
     1  1E14.4,3X4HPSI=,1F6.2//)
      WRITE(6,606)V,TAU
  606 FORMAT(1H ,30HCABLE PROPAGATION VELOCITY, V=,1P1E9.2,11HMETERS/SEC
     1,2X35HTRANSIT TIME OVER ONE CABLE LENGTH=,1E9.2,4HSEC.//)
      WRITE(6,605)NTH
  605 FORMAT(1H ,4X9HTIME(SEC),7X5HVOLTS,9X4HAMPS,5X
     116HAT CONDUCTOR NO.,I2/)
      WRITE(6,604)(T(J),VT(J),CT(J),J=1,NTIME,N)
  604 FORMAT(1P3E14.4)
      RETURN
      END
      SUBROUTINE YOYI(YO,YI,ZO,ZI,N)
C     CALLED FROM NLINE
      DIMENSION YO(1),YI(1),ZO(1),ZI(1),AI(100),AO(100)
C     SET ZI AND/OR ZO NEGATIVE (LESS THAN ZERO) TO REPRESENT OPEN
C     CIRCUIT.
      DO 5 IR=1,N
      DO 5 JC=IR,N
      NQ=N*(IR-1)+JC
      NP=N*(JC-1)+IR
      IF(ZI(NQ).LT.0.)GOTO 6
      AI(NQ)=1./ZI(NQ)
      GO TO 7
```

```
    6 AI(NQ)=0.
    7 IF(ZO(NQ).LT.0.)GOTO 8
      AO(NQ)=1./ZO(NQ)
      GO TO 9
    8 AO(NQ)=0.
    9 AI(NP)=AI(NQ)
    5 AO(NP)=AO(NQ)
      DO 10 I=1,N
      DO 10 J=I,N
      NQ=N*(I-1)+J
      NP=N*(J-1)+I
      Y1=0.
      Y2=0.
      IF(I-J)1,2,1
    2 DO 11 JJ=1,N
      JK=I
      M=N*(JK-1)+JJ
      Y1=Y1+AI(M)
   11 Y2=Y2+AO(M)
      YI(NQ)=Y1
      YO(NQ)=Y2
      GO TO 12
    1 YI(NQ)=-AI(NQ)
      YO(NQ)=-AO(NQ)
   12 YI(NP)=YI(NQ)
   10 YO(NP)=YO(NQ)
      RETJRN
      END

      SUBROUTINE TRANS(FW,FT,W,TT,IW,IT,H,KONTRL)
C     TRANS PERFORMS THE NUMERICAL FOURIER TRANSFORM OF FREQUENCY DOMAIN
C     TO TIMF DOMAIN.
C     CALLED FROM NLINE
C    FW=ARRAY OF F(W) POINTS COMPLEX     INPUT
C    FT= ARRAY OF F(T) POINTS    OUTPUT
C    W=  ARRAY OF W POINTS    INPUT
C    TT= ARRAY OF IIME POINTS    INPUT
C    IW= NUMBER OF W POINTS
C    IT= NJMBER OF TIME POINTS
C    KONTRL = .NE.0 PRINT BH,W,F(W),A,B,C.     .EQ.0  NO PRINT
      DIMENSION FT(1000),TT(1000),W(1000),A(500),B(500),C(500)
      DIMENSION G(3)
      COMPLEX FW(1000)
      DOUBLE PRECISION T,C1,C2,C3,C4,C5,C6,CS2,CSO,SN2,SNO,XP,X
      DOUBLE PRECISION W1,W2,W3,W12,W22,W32,ET1,ET2,ET3,DELTA
      G(1)=2.
      G(2)=24.
      G(3)=720.
C    ARE DIMENSIONS EXCEEDED
      IF(IW.GT.1000.OR.IT.GT.1000) GOTO1
      PI=3.1415927
      IF(KONTRL) 6,4,6
    6 WRITE(6,600)
    4 II=IW-3
      JJ=(II/2)*2
      IF(JJ.EQ.II) II=II+1
      DO5 I=1,II,2
      W1=W(I)
      W2=W(I+1)
      W3=W(I+2)
      W12=W1**2
      W22=W2**2
      W32=W3**2
      ET1=REAL(FW(I))
      ET2=REAL(FW(I+1))
      ET3=REAL(FW(I+2))
       DELTA=W22*W3-W32*W2-W12*W3+W32*W1+W12*W2-W22*W1
     L=I/2+1
     A(L)=((W2-W3)*ET1-(W1-W3)*ET2+(W1-W2)*ET3)/DELTA
     B(L)=(-(W22-W32)*ET1+(W12-W32)*ET2-(W12-W22)*ET3)/DELTA
     C(L)=((W22*W3-W32*W2)*ET1-(W12*W3-W32*W1)*ET2+(W12*W2-W22*W1)*ET3
    1     )/DELTA
     IF(KONTRL)3,5,3
   3 BH=W(I)*H/2.99E+8
     WRITE(6,601) L,BH,W(I),FW(I),A(L),B(L),C(L)
 601 FORMAT(I5,F10.6,1P2E15.3,E11.3,3E15.3)
 600 FORMAT(1H1,8X2HBH,14X1HW,13X2HRE,9X2HIM,14X1HA,14X1HB,14X1HC///)
   5 CONTINUE
     DO40 ITC=1,IT
```

```
      X=0.0                                                             TRANS049
      T=TT(ITC)                                                         TRANS050
      DO7 I=1,II,2                                                      TRANS051
      L=I/2+1                                                           TRANS052
      IF((W(I)*T).LT.1.0) GOTO41                                        TRANS053
      IF(W(I+2)*T.GE.3.3E7) GOTO40                                      TRANS054
      C1=B(L)/T**2                                                      TRANS055
      C2=2.*A(L)/T**2                                                   TRANS056
      C3=C(L)/T                                                         TRANS057
      C4=2.*A(L)/T**3                                                   TRANS058
      C5=B(L)/T                                                         TRANS059
      C6=A(L)/T                                                         TRANS060
      CS2=DCOS(W(I+2)*T)
      CS0=DCOS(W(I)*T)
      SN2=DSIN(W(I+2)*T)
      SN0=DSIN(W(I)*T)
      XP =2./PI*(C1*(CS2-CS0)+C2*(W(I+2)*CS2-W(I)*CS0)+(C3-C4)*(SN2-SN0)TRANS065
     1+C5*(W(I+2)*SN2-W(I)*SN0)+C6*(W(I+2)**2*SN2-W(I)**2*SN0))         TRANS066
      GOTO7                                                             TRANS067
   41 W1=W(I)                                                           TRANS068
      W2=W(I+2)                                                         TRANS069
      AA=A(L)                                                           TRANS070
      BB=B(L)                                                           TRANS071
      CC=C(L)                                                           TRANS072
      Q1=W1*(AA*W1**2/3. + BB*W1/2. + CC)                               TRANS073


      Q2=W2*(AA*W2**2/3. + BB*W2/2. + CC)                               TRANS074
      SUM=0.                                                            TRANS075
      IF(W1*T .LT. 0.1) GO TO 73                                        TRANS076
      DO 71 K=1,3                                                       TRANS077
      XX=K                                                              TRANS078
      S=(-1.)**K*(W1*T)**(2*K)*W1*(AA*W1**2/(3.+2.*XX)+BB*W1/(2.+2.*XX) TRANS079
     X  +CC/(1.+2.*XX))/G(K)                                            TRANS080
   71 SUM=SUM+S                                                         TRANS081
   73 TERM1=SUM+Q1                                                      TRANS082
      SUM=0.                                                            TRANS083
      IF(W2*T .LT. 0.1) GO TO 83                                        TRANS084
      DO 81 K=1,3                                                       TRANS085
      XX=K                                                              TRANS086
      S=(-1.)**K*(W2*T)**(2*K)*W2*(AA*W2**2/(3.+2.*XX)+BB*W2/(2.+2.*XX) TRANS087
     X  +CC/(1.+2.*XX))/G(K)                                            TRANS088
   81 SUM=SUM+S                                                         TRANS089
   83 TERM2=SUM+Q2                                                      TRANS090
      XP=2./PI*(TERM2-TERM1)                                            TRANS091
    7 X=X+XP                                                            TRANS092
   40 FT(ITC)=X                                                         TRANS093
      RETURN                                                            TRANS094
    1 WRITE(6,610) IW,IT                                                TRANS095
  610 FORMAT(34H DIMENSIONS OF TRANS ARE EXCEEDED.////4H IW=,I6,4H IT=, TRANS096
     I    I6////14H CALLING DUMP./ )                                    TRANS097
      STOP                                                              TRANS099
      END                                                               TRANS100
```

7. INPUT DATA FORMAT

A summary of the order and format by which data are read into NLINE is given in FORTRAN statements below.

```
          READ(5,5000)A,A1,A2
          READ(5,5001)PERCEN
          READ(5,505)(COMNT(MN),MN=1,8)
          READ(5,500)MSETS,NWIRES
          READ(5,501)(CMAXWL(J),J=1,NCAPS)
          READ(5,503)(ELI(J),J=1,NP)
          READ(5,504)IQ

          DO88 JJ88=1,MSETS

          READ(5,501)(ZI(J),J=1,N2)
          READ(5,501)(ZO(J),J=1,N2)
          READ(5,502)PSI,TL

       88 CONTINUE
     5000 FORMAT(3E10.0)
     5001 FORMAT(F5.0)
      505 FORMAT(8A10)
      500 FORMAT(2I5)
      501 FORMAT(8E10.0)
      504 FORMAT(I5)
      502 FORMAT(2F10.0)
```

where, NCAPS = NWIRES*(NWIRES + 1)/2, NP = WIRES-1, and N2 = NP*NP.

A listing of a sample data set consisting of 10 data cards follows. The FORTRAN card columns are indicated.

```
Data Card Columns:
1   5   10         20        30         40         50         60
I   I    I          I         I          I          I          I
I   I    I          I         I          I          I          I
I   I  1.+2       3.+6      5.+8         I          I          I
I  .7                                    I          I          I
**NLINE STANDARD DECK**                  I          I          I
    1    3                               I          I          I
       1.+0       1.+0      1.+0   3.279-11  -1.704-11  3.279-11
    3.74-7     1.58-7
    1
       1.+2       1.+2      1.+2       1.+2
       1.+2       1.+2      1.+2       1.+2
         90        30.
```

8. OUTPUT FORMAT

NLINE output in the Standard Deck is in line-printer form. The user may add optional plotting instructions at the locations indicated in the deck. Frequency-domain results are printed out when the subroutine HEAD is called. Time-domain results are printed out when the subroutine HTTM is called. The control parameter J in the listing is used to limit lines printed if other forms of output, such as tapes or plots, are used. Informative comments are included in the listings of the two subroutines.

Figures 3 through 7 show samples of a typical NLINE printout. This printout is generated when the NSD is run with the sample data listed in section 7.

Figure 3 shows the first page of the output, where several arrays of interest are printed in linear form (*i.e.*, the ZI array shows values of Z^L_{11}, Z^L_{12}, Z^L_{21}, Z^L_{22}). ZI and ZO are the terminating impedance arrays defined in section 4. LE is the magnetic-field coupling parameter vector. YI and YO are defined by equations (19) and (20). CC is the Maxwell capacitance coefficient array. C is the Maxwell capacitance array after the i^{th} row and i^{th} columns have been deleted from CC, the i^{th} conductor being the reference conductor. C^- is the matrix inverse of C. Y and Z are defined in equations (15). PO and PI are defined in equations (17) and (18), respectively.

Figure 4 shows the second page of the output for this run. The radian frequency, amplitude, and phase of the voltage induced on each conductor (see listing for subroutine HEAD for printout instructions of the current, if desired). For example, the first frequency is 1.1×10^4 rad/s and the voltage magnitude on conductor 1 is 4.94×10^{-9} V, the phase is given directly below, marked by "ARG", and has the value of 270 deg. Similarly, in column "2", the voltage and phase induced on conductor 2 is given as 2.09×10^{-9} at 270 deg, respectively.

Figures 5 and 6 show printouts of the time-domain voltages and currents induced on conductors 1 and 2, respectively. The heading indicates that the computations were made at $x = 0$, on a transmission line of length $l = 30$ m, with angle of incidence $\psi = 90$ deg. Cable propagation velocity and transit time over one cable length are also printed.

Figure 7 shows printouts of the incident electric field used for the computations. The exact time-domain value of the field is obtained from subroutine TEMPLT, and is printed in column "EXACT." The column "TRANSFORM" gives the results from the NLINE numerical transform of the frequency-domain electric field obtained from subroutine HZFREE. The close agreement for most of the values indicates the relative accuracy of the numerical transformation.

```
**NLINE STANDARD DECK**

ZI
  .100E+03   .100E+03   .100E+03   .100E+03
ZO
  .100E+03   .100E+03   .100E+03   .100E+03
LE
   .374E-06   .158E-06
YO
  .200E-01  -.100E-01  -.100E-01   .200E-01
YI
  .200E-01  -.100E-01  -.100E-01   .200E-01
CC
  .100E+01   .100E+01   .100E+01   .100E+01   .328E-10  -.170E-10   .100E+01  -.170E-10   .328E-10
C
  .328E-10  -.170E-10  -.170E-10   .328E-10
C-
  .418E+11   .217E+11   .217E+11   .418E+11
Y
  .689E-02  -.358E-02  -.358E-02   .689E-02
Z
  .199E+03   .103E+03   .103E+03   .199E+03
PO
  .295E+01   .783E-01   .783E-01   .295E+01
PI
  .295E+01   .783E-01   .783E-01   .295E+01
```

Figure 3. Sample NLINE output (first page).

I.D.= 4056001 **NLINE STANDARD DECK** I.D.= 4066001

VOLTAGES AT X=0.00*LINE LENGTH L= .3000E+02 PSI= 90.00

RAD/SEC	CONDUCTOR 1	2	3	4	5	6	7	8	9	10
.11E+05	.494E-08	.209E-06								
ARG	.270E+03	.270E+03								
.35E+05	.163E-07	.690E-08								
ARG	.269E+03	.269E+03								
.61E+05	.277E-07	.117E-07								
ARG	.268E+03	.268E+03								
.86E+05	.391E-07	.165E-07								
ARG	.265E+03	.268E+03								
.12E+06	.539E-07	.228E-07								
ARG	.267E+03	.267E+03								
.37E+05	.167E-05	.705E-07								
ARG	.261E+03	.260E+03								
.62E+05	.277E-06	.117E-06								
ARG	.254E+03	.254E+03								
.87E+05	.384E-06	.162E-06								
ARG	.248E+03	.247E+03								
.12E+07	.513E-06	.216E-06								
ARG	.240E+03	.239E+03								
.37E+07	.106E-05	.437E-06								
ARG	.187E+03	.166E+03								
.62E+07	.102E-05	.415E-06								
ARG	.153E+03	.151E+03								
.87E+07	.839E-06	.339E-06								
ARG	.131E+03	.130E+03								
.12E+08	.641E-06	.258E-06								
ARG	.114E+03	.113E+03								
.37E+08	.166E-06	.676E-07								
ARG	.533E+02	.547E+02								
.62E+08	.113E-06	.454E-07								
ARG	.858E+02	.855E+02								
.87E+08	.170E-07	.717E-08								
ARG	.358E+03	.359E+03								
.12E+09	.554E-07	.223E-07								
ARG	.556E+02	.564E+02								
.37E+09	.148E-07	.593E-08								
ARG	.406E+02	.403E+02								
.62E+09	.399E-08	.165E-08								
ARG	.582E+02	.567E+02								
.87E+09	.298E-08	.120E-08								
ARG	.327E+03	.328E+03								

Figure 4. Sample NLINE frequency-domain output (second page).

I.D.= 4066002 **NLINE STANDARD DECK** I.D.= 4066002

RESPONSE AT X=0.00*LINE LENGTH L= .3000E+02 PSI= 90.00

CABLE PROPAGATION VELOCITY, V= 2.10E+08METERS/SEC, TRANSIT TIME OVER ONE CABLE LENGTH= 1.43E-07SEC.

TIME(SEC)	VOLTS	AMPS	AT CONDUCTOR NO. 1
1.0000E-12	-3.5820E-01	5.7100E-03	
2.8551E-09	-2.9779E+00	4.7465E-02	
5.7153E-09	-4.8067E+00	7.5619E-02	
2.2715E-08	-5.2322E+00	8.3406E-02	
5.1287E-09	-4.8908E+00	7.7989E-02	
7.9855E-08	-4.8360E+00	7.7080E-02	
1.0843E-07	-4.5002E+00	7.1718E-02	
1.3700E-07	-4.0672E+00	6.4824E-02	
1.6557E-07	-1.0859E+00	1.6880E-02	
1.9414E-07	-7.6236E-01	1.1749E-02	
2.2272E-07	-6.7466E-01	1.0355E-02	
2.5129E-07	-4.9944E-01	7.5064E-03	
2.7986E-07	-2.8673E-01	4.2220E-03	
3.0843E-07	1.0957E+00	-1.7764E-02	
3.3700E-07	1.1207E+00	-1.8136E-02	
3.6557E-07	1.0602E+00	-1.7145E-02	
3.9414E-07	1.0103E+00	-1.6330E-02	
4.2272E-07	1.0590E+00	-1.7060E-02	
4.5129E-07	1.5837E+00	-2.5300E-02	
4.7986E-07	1.4733E+00	-2.3533E-02	
5.0843E-07	1.3402E+00	-2.1387E-02	
5.3700E-07	1.2097E+00	-1.9309E-02	
5.6557E-07	1.2005E+00	-1.9127E-02	
5.9414E-07	1.3361E+00	-2.1194E-02	
6.2272E-07	1.2211E+00	-1.9370E-02	
6.5129E-07	1.0834E+00	-1.7169E-02	
6.7986E-07	9.6901E-01	-1.5358E-02	
7.0843E-07	9.4423E-01	-1.4943E-02	

Figure 5. Sample NLINE time-domain output (third page).

I.D.= 4056003 **NLINE STANDARD DECK** I.D.= 4066003

RESPONSE AT X=0.00*LINE LENGTH L= .3000E+02 PSI= 90.00

CABLE PROPAGATION VELOCITY, V= 2.10E+08METERS/SEC, TRANSIT TIME OVER ONE CABLE LENGTH= 1.43E-07SEC.

TIME(SEC)	VOLTS	AMPS	AT CONDUCTOR NO. 2
1.0000E-12	-1.4536E-01	-6.7474E-04	
2.8581E-09	-1.2092E+00	-5.5950E-03	
5.7153E-09	-1.9515E+00	-9.0367E-03	
2.2715E-08	-2.1238E+00	-9.8456E-03	
5.1287E-08	-1.9828E+00	-9.2525E-03	
7.9858E-08	-1.9640E+00	-9.0794E-03	
1.0843E-07	-1.8285E+00	-8.4305E-03	
1.3700E-07	-1.6520E+00	-7.6319E-03	
1.6557E-07	-4.8376E-01	-1.1835E-03	
1.9414E-07	-3.4984E-01	-6.2685E-04	
2.2272E-07	-3.1384E-01	-4.5992E-04	
2.5129E-07	-2.4025E-01	-1.8941E-04	
2.7986E-07	-1.5127E-01	1.5801E-04	
3.0843E-07	4.1505E-01	2.6562E-03	
3.3700E-07	4.2818E-01	2.6453E-03	
3.6557E-07	4.0584E-01	2.4851E-03	
3.9414E-07	3.8750E-01	2.3527E-03	
4.2272E-07	4.1190E-01	2.3516E-03	
4.5129E-07	6.3728E-01	3.0910E-03	
4.7986E-07	5.9318E-01	2.8691E-03	
5.0843E-07	5.4170E-01	2.5678E-03	
5.3700E-07	4.8839E-01	2.3287E-03	
5.6557E-07	4.8835E-01	2.2381E-03	
5.9414E-07	5.5285E-01	2.3040E-03	
6.2272E-07	5.0533E-01	2.1049E-03	
6.5129E-07	4.4998E-01	1.8349E-03	
6.7986E-07	4.0223E-01	1.6454E-03	
7.0843E-07	3.9414E-01	1.5596E-03	

Figure 6. Sample NLINE time-domain output (fourth page).

I.D.= 4066003 **NLINE STANDARD DECK** I.D.= 4066003

INCIDENT ELECTRIC FIELD FROM EXACT EQUATION AND FROM FOURIER TRANSFORM IN VOLTS/METER

TIME(SEC)	EXACT	TRANSFORM
1.0000E-12	2.4596E-05	7.0230E+00
2.8581E-09	5.9657E+01	5.7101E+01
5.7153E-09	9.1186E+01	9.1883E+01
2.2715E-08	9.5454E+01	9.9369E+01
5.1287E-08	9.5964E+01	9.5765E+01
7.9858E-08	9.0800E+01	9.0576E+01
1.0843E-07	8.4530E+01	8.4395E+01
1.3700E-07	7.7943E+01	7.7702E+01
1.6557E-07	7.1091E+01	7.0848E+01
1.9414E-07	6.4323E+01	6.4078E+01
2.2272E-07	5.7807E+01	5.7561E+01
2.5129E-07	5.1652E+01	5.1405E+01
2.7986E-07	4.5923E+01	4.5673E+01
3.0843E-07	4.0652E+01	4.0405E+01
3.3700E-07	3.5849E+01	3.5602E+01
3.6557E-07	3.1506E+01	3.1259E+01
3.9414E-07	2.7605E+01	2.7360E+01
4.2272E-07	2.4122E+01	2.3877E+01
4.5129E-07	2.1026E+01	2.0783E+01
4.7986E-07	1.8287E+01	1.8045E+01
5.0843E-07	1.5872E+01	1.5631E+01
5.3700E-07	1.3751E+01	1.3511E+01
5.6557E-07	1.1892E+01	1.1655E+01
5.9414E-07	1.0269E+01	1.0033E+01
6.2272E-07	8.8543E+00	8.6198E+00
6.5129E-07	7.6242E+00	7.3912E+00
6.7986E-07	6.5567E+00	6.3255E+00
7.0843E-07	5.6320E+00	5.4026E+00

Figure 7. Sample NLINE incident EMP output (fifth page).

9. SAMPLE PROBLEM

This sample problem is compatible with the NLINE Standard Deck listing and with the sample data set included in this manual. The procedure for solving a typical transmission-line problem with NLINE is outlined in this section and computation of EMP coupling with a configuration of three parallel conduits is described. The EMP environment and the environment orientation with respect to the conductors are assumed known.

The conductor cross section for the sample problem is shown in figure 8.

For the sample problem, the EMP is defined to arrive at broadside incidence ($\psi = 90$ deg). Thus, the magnetic and the electric fields are oriented entirely along the Z and X directions. The Poynting vector $\vec{P}$ is oriented in the minus-$\hat{y}$ direction, as shown in figure 8. A specific orientation of the magnetic field H_z^e with respect to the conductor cross section determines a unique set of values for the magnetic-field coupling parameters $\underline{L}^e$ (eq. (10)).

The conductor length is chosen to be 30 m and all terminations are chosen to be 100 ohms. The propagation velocity among the conductors is chosen to be 70% of the free space velocity of light. This is a typical value for propagation along many classes of transmission lines analyzed in nuclear EMP technology. The point of computation of currents and voltages is chosen at the $x = 0$ end of the conductors. Pulse(-1) is used for this run. The thin-wire approximations are used to obtain the Maxwell's capacitance coefficients and magnetic-field coupling parameters.[2]

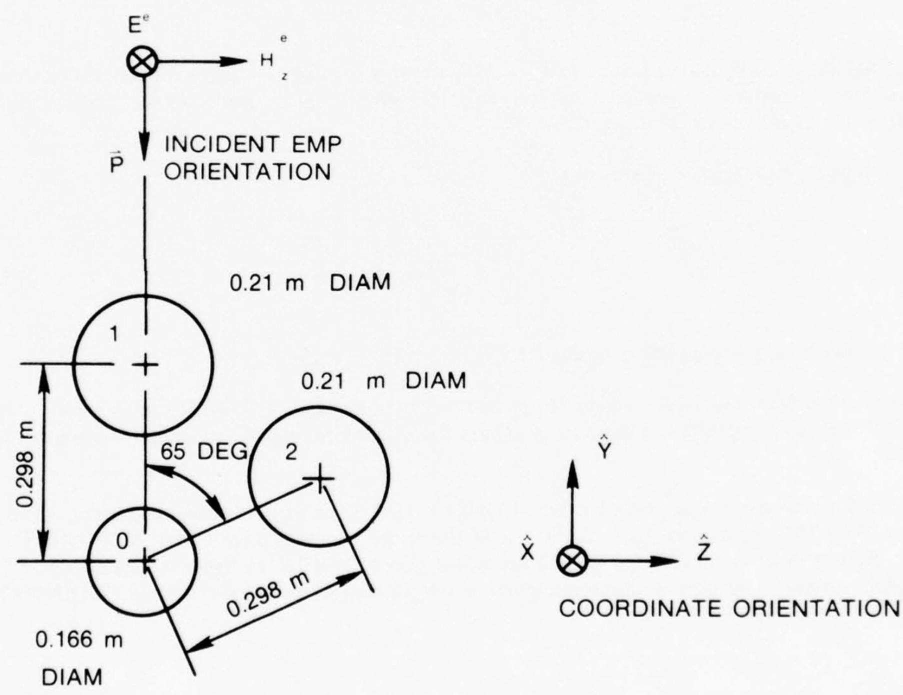


Figure 8. Sample problem conductor cross section, and orientation with respect to the incident EMP.

[2] Janis Klebers, *Electromagnetic Pulse Coupling with Lossless Multiconductor Transmission Lines*, Harry Diamond Laboratories TR-1711 (June 1975).

The sample problem parameters are summarized below.

(a) Incident EMP: Pulse(-1).
(b) Angle of incidence: $\psi = 90$ deg.
(c) Orientation of H_z^e: as shown in figure 8.
(d) Conductor length: $\ell = 30$ m.
(e) Conductor propagation velocity: $v = 2.1 \times 10^8$ m/s.
(f) Conductor terminations (chosen identically at $x = 0$ and $x = \ell$): $Z_{11} = Z_{12} = Z_{22} = 100$ ohms, connected as shown in figure 1.
(g) Reference conductor designated as the zero-th conductor, 0.
(h) The Maxwell's capacitance coefficient matrix:

$$\underline{C} = \begin{bmatrix} 1.^* & 1.^* & 1.^* \\ 1.^* & 32.8 & -17.0 \\ 1.^* & -17.0 & 32.8 \end{bmatrix} \text{ pf/m} \tag{25}$$

*Arbitrary capacitance values have been listed for the reference conductor, since NLINE uses only the reduced capacitance matrix for these computations:

$$\underline{C}' = \begin{bmatrix} 32.8 & -17.0 \\ -17.0 & 32.8 \end{bmatrix} \text{ pf/m} \tag{26}$$

The full capacitance matrix is read into NLINE, allowing the user to change the reference conductor. In that case, the values for *all* capacitances including the reference conductor must, of course, be included correctly in the capacitance matrix (eq. (25)).

(i) The magnetic-field coupling parameters:

$$\underline{L}^e = \begin{bmatrix} 3.74 \\ 1.58 \end{bmatrix} \times 10^{-7} \text{ H} \tag{27}$$

$\underline{C}'$ and $\underline{L}^e$ have been computed by program PTNTL, listed in appendix A.

The NLINE Standard Deck accepts all the above parameters and performs the computations. The NSD printout of this sample problem was given in section 8. Figures 9 through 13 show optional plotter output of the results.

Figure 9 shows the results printed under "CONDUCTOR 1" in figure 4. Results in figure 10 correspond with the "VOLTS" column in figure 5. Figure 11 shows the results printed under "CONDUCTOR 2" in figure 4. Results in figure 12 correspond with the results under "VOLTS" in figure 6. Finally, figure 13 shows the incident electric field used in the computation, corresponding to the column labeled "TRANSFORM" in figure 7.

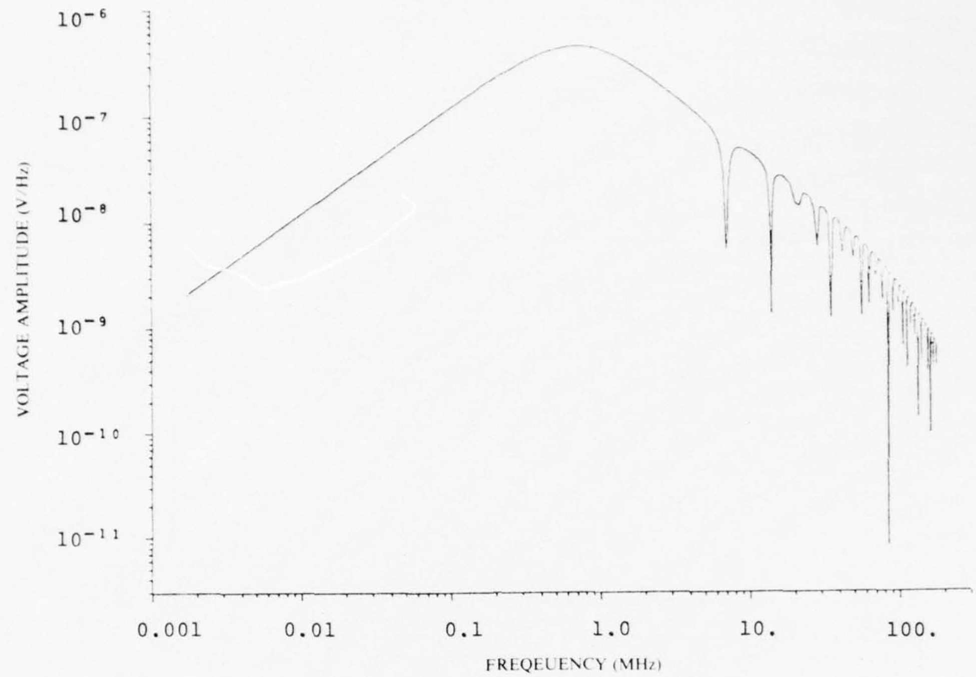


Figure 9. SAMPLE PROBLEM: Frequency-domain plot of voltage induced on conductor No. 1 by Pulse(-1).

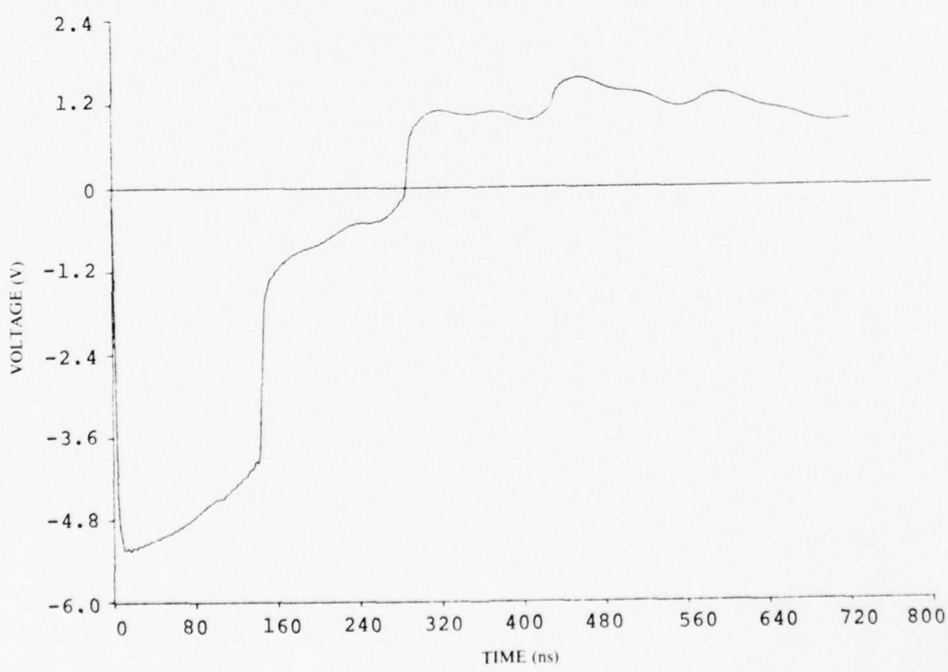


Figure 10. SAMPLE PROBLEM: Time-domain plot of voltage induced on conductor No. 1 by Pulse(-1).

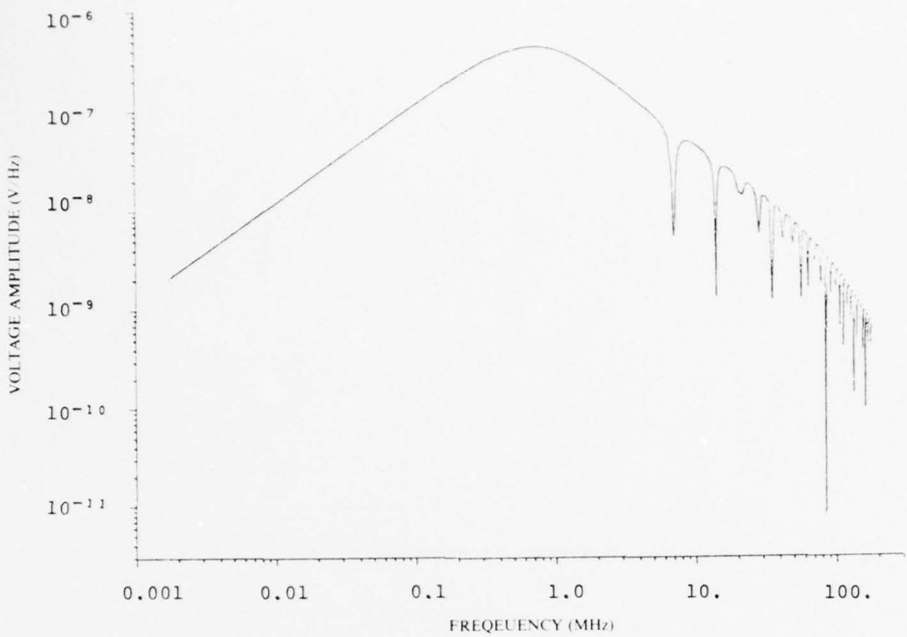


Figure 11. SAMPLE PROBLEM: Frequency-domain plot of voltage induced on conductor No. 2 by Pulse(-1).

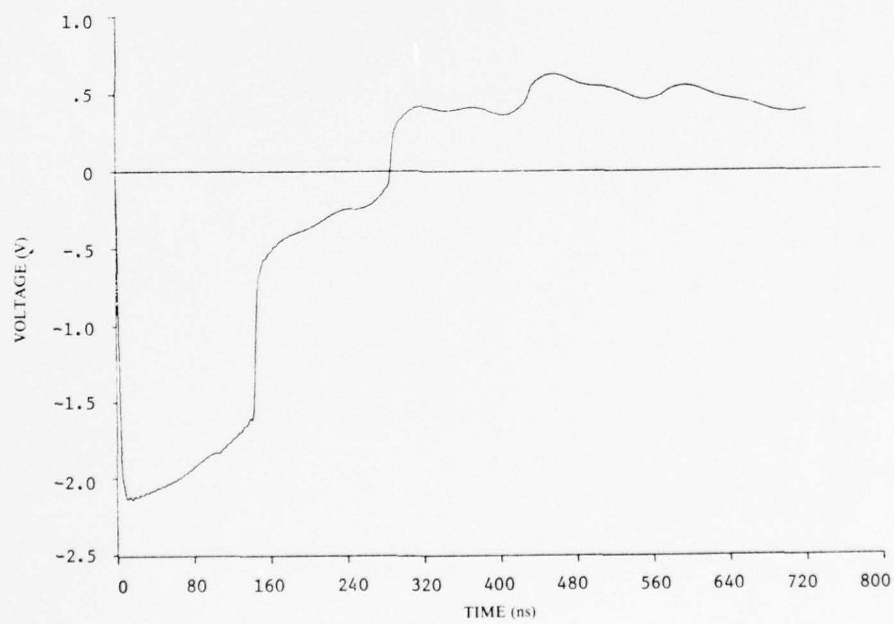


Figure 12. SAMPLE PROBLEM: Time-domain plot of voltage induced on conductor No. 2 by Pulse(-1).

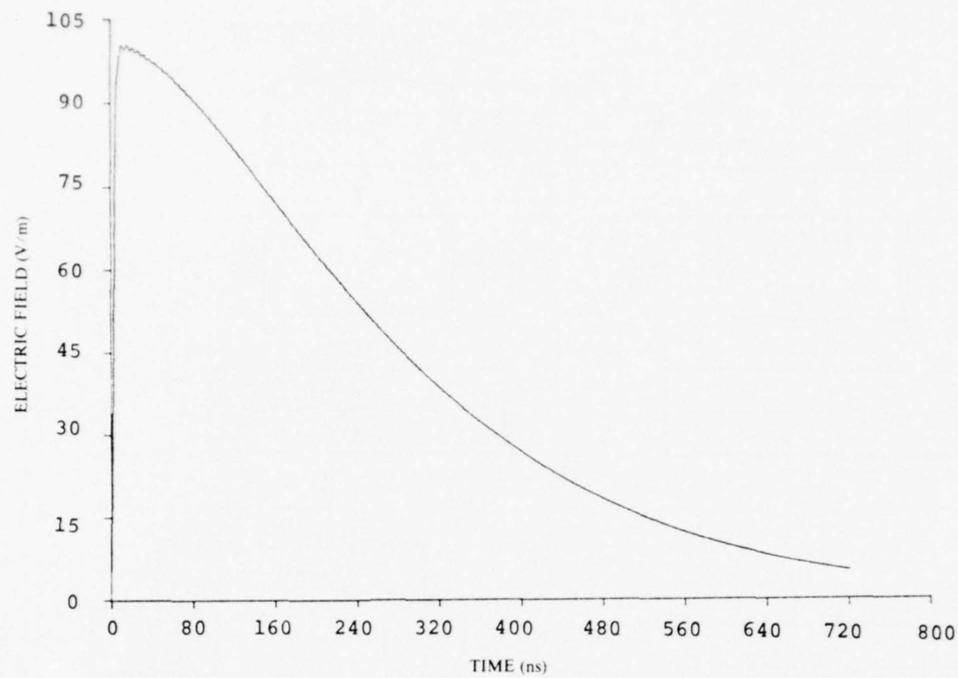


Figure 13. INCIDENT EMP FOR SAMPLE PROBLEM: Time-domain plot of Pulse(-1) obtained by numerical Fourier transform from the frequency-domain expression.

10. NLINE APPLICATIONS: INTRODUCTION OF NONLINEAR LOADS BY LUMPED-PARAMETER NETWORK SYNTHESIS.

For many NLINE computations for cables in Army systems, it is sufficient to represent the terminations of the multiconductor transmission line by "open," "short," or "matched" resistive loads (*i.e.*, load resistance large compared to the characteristic line impedance, load resistance small compared to the characteristic line impedance, or load resistance close to the characteristic line impedance). Direct computations of current and voltage are made by NLINE for the above types of problems. Nonlinear loads, such as terminal protection devices, surge arrestors, and other electrical circuits may be added by incorporating the NLINE output with circuit analysis codes—such as DAMTRAC—used at HDL.[5] The NLINE code represents the solution for the transmission-line response due to a *continuously* distributed EMP excitation. The NLINE output is not directly compatible with typical circuit analysis codes in this form since the circuit analysis codes require *discrete* lumped-parameter circuits and *discrete* current or voltage sources as input parameters.

Figure 14 shows symbolically the method employed to convert the continuous source output from the transmission-line theory to the equivalent discrete voltage source and lumped-parameter network. The approach is to obtain the Thévenin voltage and circuit for the particular transmission line and for the particular EMP illumination. Once this has been done, the load can be arbitrarily specified at one end of the transmission line. In particular, complex circuits can be attached to the transmission line at this end and the response can be computed by circuit analysis codes. By this method, the other end of the transmission line must still have real loads compatible with the NLINE Standard Deck. The outline below summarizes the NLINE computations required for the network synthesis.

[5] G. Baker, A. McNutt, B. Shea, D. Rubenstein, *Damage Analysis Modified TRAC Computer Program (DAMTRAC)*, Harry Diamond Laboratories TM-75-6 (May 1975)

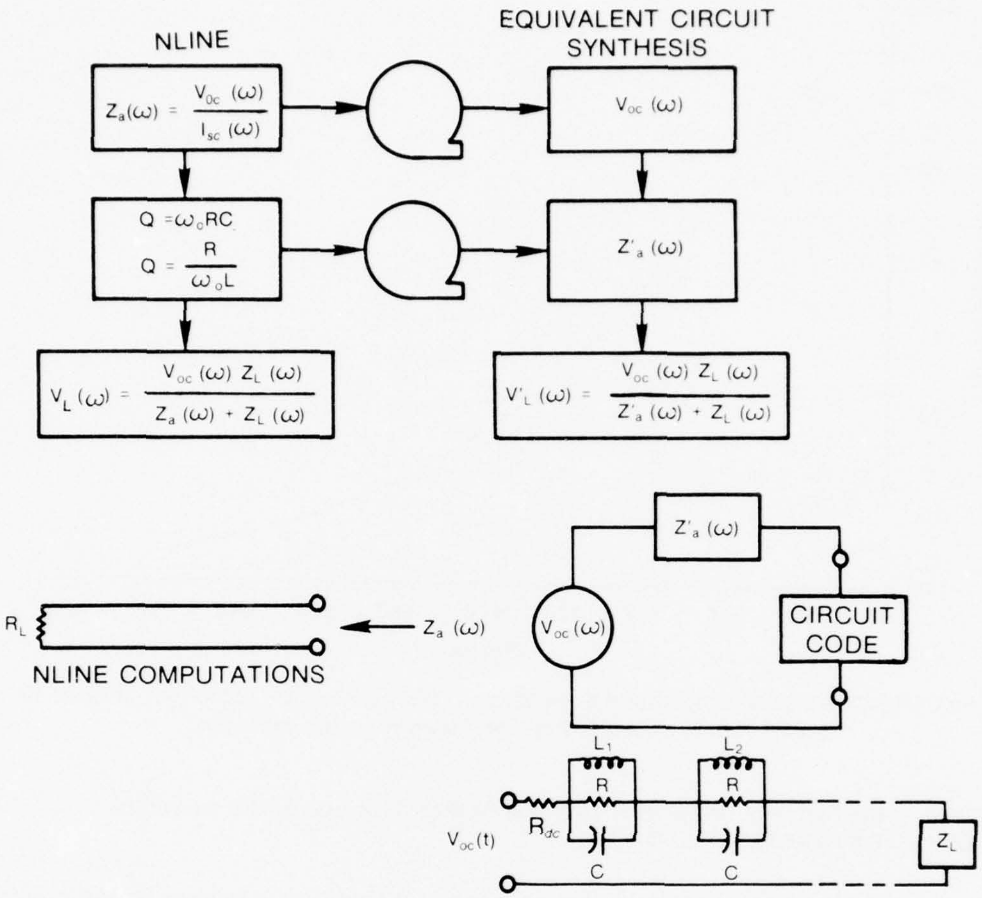


Figure 14. Lumped-parameter network synthesis by NLINE computations.

NLINE THÉVENIN EQUIVALENT CIRCUIT METHODS FOR USE WITH CIRCUIT ANALYSIS CODES AND NONLINEAR LOADS AT ONE END OF THE TRANSMISSION LINE

(a) Specify all NLINE input parameters for the particular problem.

(b) Designate *one end* of the transmission line (*i.e.*, $x = 0$ or $x = \ell$) where complex load conditions are to be analyzed.

(c) Specify loads at the *other end* of the transmission line which best approximate the actual terminating conditions and are compatible with the NSD (*i.e.*, real loads having values best approximated to be large, intermediate, equal, or small compared to the transmission-line impedance).

(d) Leaving the above parameters fixed, use NLINE to compute the open circuit voltage and the short circuit current at the *circuit end*. To accomplish this, run NLINE once with arbitrary negative values of load impedances at the *circuit end* (NLINE treats negative terminating resistance values as open circuits). Store the open circuit voltages $V_{oc}(\omega)$ on tape. Next, compute the short circuit current $I_{sc}(\omega)$, with small (*e.g.*, 1 ohm or less) values for the terminations at the circuit end, and store on tape.

(e) Compute the transmission-line impedance $Z_a(\omega)$ by

$$Z_a(\omega) = \frac{V_{oc}(\omega)}{I_{sc}(\omega)} . \qquad (28)$$

(f) Construct an equivalent circuit with lumped parameters for $Z_a(\omega)$. For broadside EMP incidence, ψ = 90 deg, $|Z_a(\omega)|$ clearly exhibits the impedance characteristics of a series of parallel R-L-C circuits whose component values are determined from the Quality Factor, Q, which is obtained from $|Z_a(\omega)|$. Q is determined from the fundamental resonant frequency f_o of $|Z_a(\omega)|$ and the corresponding half-power frequencies f_1 and f_2 from[6]

$$Q = \frac{f_o}{2(f_2 - f_1)}, \; f_2 > f_1 . \qquad (29)$$

Knowing Q, the values of R, L, and C are determined from

$$Q = \omega_o R C$$
$$\qquad (30)$$
$$Q = \frac{R}{\omega_o L} .$$

The equivalent lumped-parameter circuit is constructed from a series of R-L-C circuits, as shown in figure 14, where the value of L is varied, holding R and C constant. Generally, a low-frequency element must be included to account for the low-frequency characteristics of $|Z_a(\omega)|$. For the following example, this component is a resistance R_{dc}. The values of L are chosen so that each tank circuit resonates at the odd harmonics of f_o. Hence, the values of L_i are

$$L_i = \frac{L_o}{m_i}, m_i = 1,3,\ldots, \text{odd} \qquad (31)$$

and $i = 1,2,\ldots,N_c$, where N_c is the number of tank circuits used in the synthesis. L_o is determined from Q, R, and ω_o in the second of equations (30). The larger the value of N_c used, the higher the high-frequency cutoff point beyond which the transmission line is no longer adequately represented by the lumped-parameter model.

The input impedance $Z_a'(\omega)$ of the equivalent lumped-parameter circuit approximates very closely the transmission-line impedance $Z_a(\omega)$ for frequencies less than the high frequency cutoff. Hence, $Z'_a(\omega)$ can be used to replace the continuous-source transmission-line impedance by a specified series of R-L-C tank circuits programable into circuit analysis codes.

(g) The load voltage at the *circuit end*, due to an arbitrary load, Z_L, can now be computed from

$$V_L(\omega) = \frac{V_{oc}(\omega) Z_L(\omega)}{Z_a(\omega) + Z_L(\omega)} \qquad (32)$$

or from:

$$V'_L(\omega) = \frac{V_{oc}(\omega) Z_L(\omega)}{Z'_a(\omega) + Z_L(\omega)} . \qquad (33)$$

Equations (32) and (33) describe Thévenin equivalent circuits for the transmission line.

[6] R. E. Collin, *Foundations for Microwave Engineering*, McGraw-Hill Book Co., NY (1966), 314-315.

(h) As a final step, $V_{oc}(\omega)$ is transformed to the time domain. Z_L is programmed in the circuit analysis code along with the lumped-parameter representation of Z'_a and the time domain representation of V_{oc}. The problem is solved in the time domain by the circuit analysis code.

The NLINE Standard Deck was modified to perform the above steps. The *sample problem* data parameters were used for the computations. Figures 15 and 16 show the open circuit voltage and the short circuit current, respectively. The transmission-line impedance computed by NLINE is shown in figure 17. The corresponding result for the lumped-parameter model appears in figure 18. Twenty R-L-C circuits were used, giving a high-frequency cutoff at 70 MHz. A higher cutoff can be attained by increasing the number of circuits used in the model.

Equation (33) is used to test the accuracy of the model. Figure 19 shows the voltage on Conductor No. 1 of the sample problem computed from the lumped-parameter model. Comparison of this result with the result from figure 10 shows that the lumped-parameter model gives a relatively accurate representation of the transmission-line response. The frequency and time arrays are selected in the NSD on the basis of transmission-line length and on five transit times of the pulse as it is reflected back and forth along the transmission line. Some of the high-frequency spikes appearing in the lumped-parameter results are due to the numerical Fourier transform "noise," and can be corrected by a choice of more appropriate frequency and time points in the transform. In general, an optimum frequency and time-array selection scheme is not available for a fixed number of points (600 in the NSD) and for a wide range of transmission-line lengths. Guidance on numerical transforms is given in the DNA EMP Handbook,[7] and should be used to select the frequency and time arrays appropriate for a specific problem. When properly used, the lumped-parameter technique provides a useful application of the NLINE code for problems where circuit analysis codes must be used to treat EMP coupling with transmission lines terminated into complex circuits.

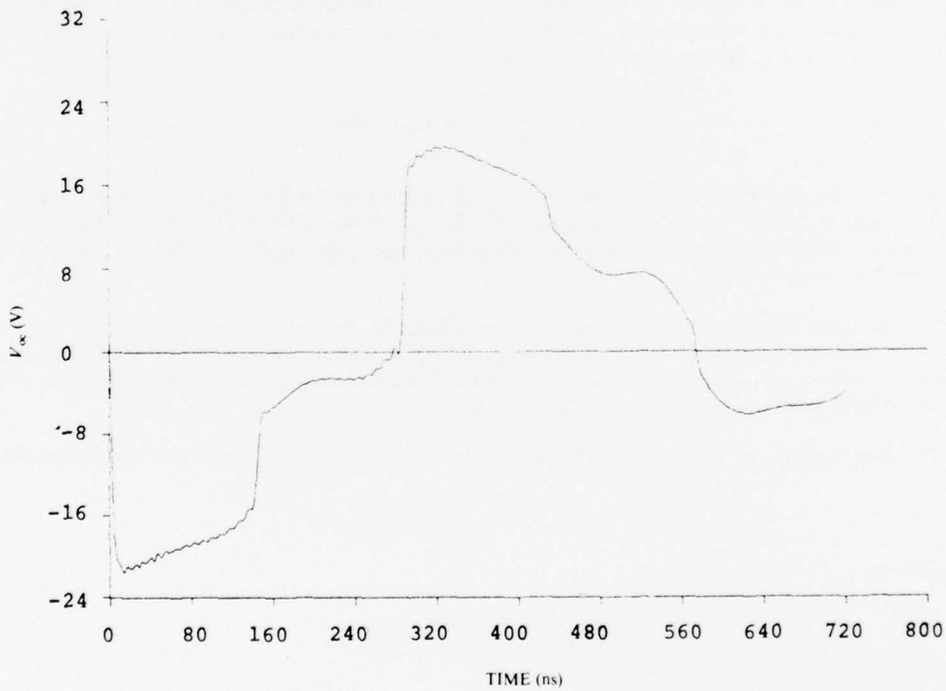


Figure 15. Open-circuit voltage computed by NLINE for use with the lumped-parameter network model.

[7] R. L. Hutchins, Defense Nuclear Agency EMP Handbook Chapter 14: EMP Data Analysis, BDM/A-135-75-TR-R1, 24 Sept 1975.

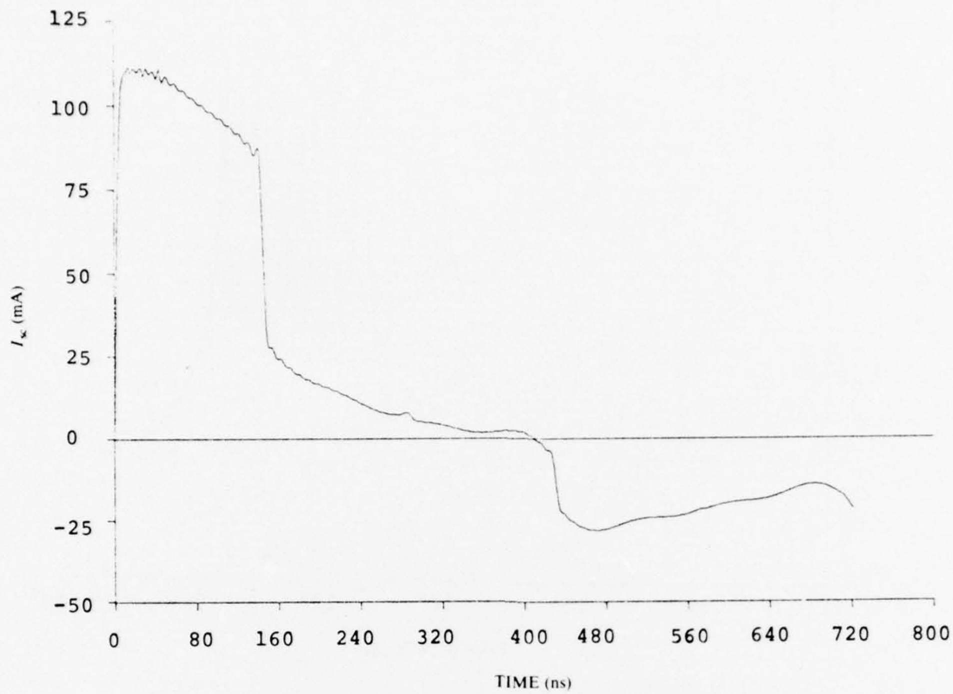


Figure 16. Short-circuit current computed by NLINE for use with the lumped-parameter network model.

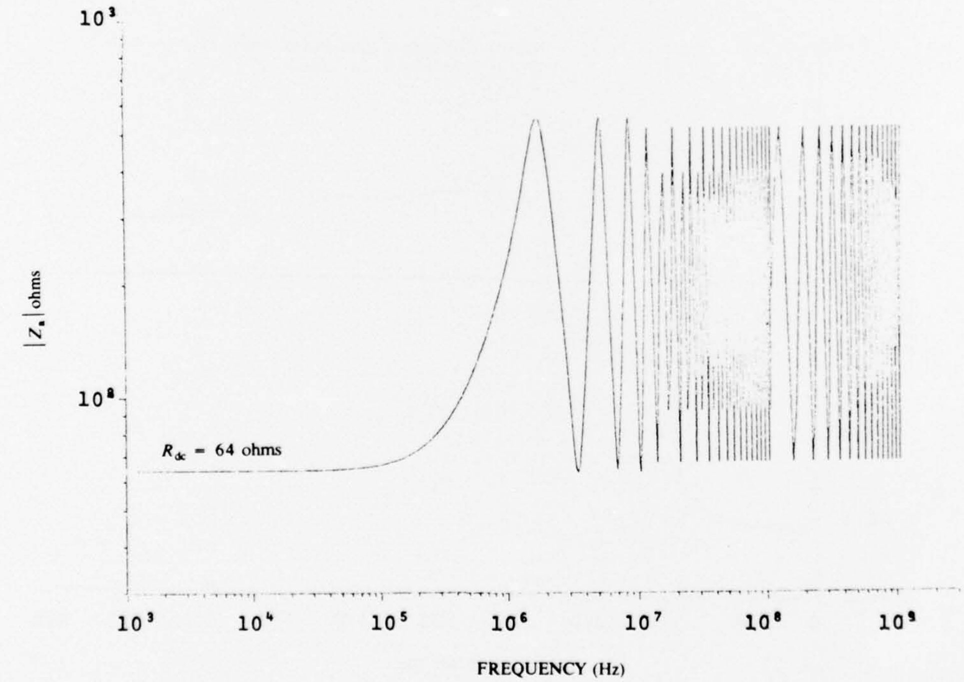


Figure 17. Transmission-line impedance computed by NLINE—l = 30 m, ψ = 90 deg, Q = 1.16.

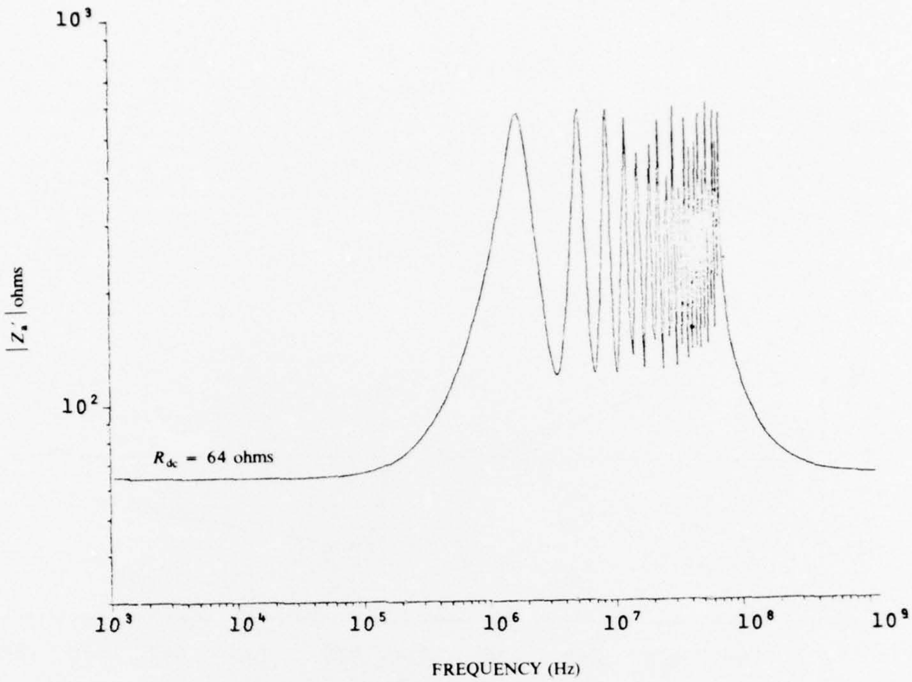


Figure 18. *Equivalent lumped-parameter network transmission-line impedance obtained from 20 R-L-C circuits*—ℓ = 30 m, ψ = 90 deg, Q = 1.19.

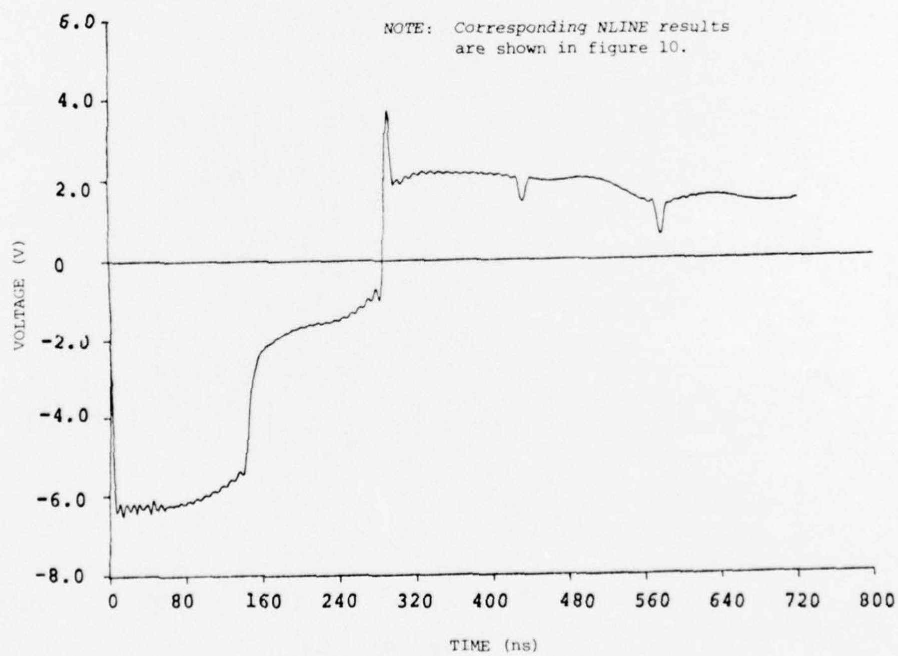


Figure 19. Time-domain plot of voltage induced on conductor No. 1; computed from the lumped-parameter network model.

II. APPLICATION OF NLINE TO REAL CABLES: COMPARISON OF NUMERICAL PREDICTIONS WITH MEASURED RESULTS.

The NLINE code is designed to predict nuclear or simulator generated EMP coupling with cables used in systems under EMP evaluation. A confidence level must be established for the NLINE computations in order for the code to be successfully applied. The AESOP radiating-dipole EMP facility at HDL was used to obtain experimental coupling data for comparison with NLINE predictions. The results of that test are discussed in this section following a summary of important aspects to be considered when applying NLINE to real cables.

The NLINE code requires several input parameters discussed in previous sections which either must be determined experimentally or computed by approximate methods for complex cables. How accurately these parameters are specified for the experimental conditions ultimately determines how well NLINE computations agree with measured results. The accuracy in measuring differential voltages or currents in the radiated EMP experimental environment also can be expected to vary with the type of cable tested and instrumentation problems (*e.g.*, common-mode rejection capability, low signal level, etc.) encountered in the experiment. The above factors can be expected to produce differences between the computed and measured results.

Coupling measurements and NLINE computations are presented in this section for 3-m-long transmission-line samples made up of three and eleven conductors illuminated by the AESOP environment. Determination of the coupling parameters for these cables has been discussed.[2] The cables were oriented in the test area parallel to the AESOP antenna, and were located 0.35 m above ground at a range of 75 m on the center-line. The significant differential-mode coupling is due only to the radial component of the AESOP magnetic field in this configuration. Figure 20 shows the radial magnetic-field component, along with the Pulse(−1) approximation used in NLINE for the computations. The general waveshape and peak amplitude for Pulse(−1) adequately represent the AESOP pulse. The early time ramp and the irregular plateau characteristics have not been included in the curve fit. Some error results from these omissions. To eliminate this type of error, the user can modify COMPLEX FUNCTION HZFREE in NLINE to return the exact frequency characteristics of the measured environment.

Unshielded transmission lines made up of two and three conductors represent an important class of interest for nuclear EMP analysis. A very large group of Army systems uses these types of transmission lines for communication and power-transmission. The NLINE code can be used with a high confidence level for these types of cables. Figure 21 shows the measured and computed results for the three-conductor test sample. The peak values agree very closely, but more ringing appears in the measurement than in the computation of the load current. This is probably due to the reactive load/instrumentation conditions existing in the experiment which are not accounted for in the lossless NLINE model.

The increase in the number of conductors in the transmission line increases the margin of expected difference between predictive computations and measurements. The decrease in accuracy for determining the coupling parameter values and increased lossy conditions in the cable can account for this difference.

Figure 22(a) shows the eleven-conductor sample cross-section with the computed and measured coupling parameters listed by each conductor. Agreement is not always good between the experimental and numerical methods employed here. Admittedly, more accurate means are available for the user to determine the parameters. The thin-wire approximations are used here to demonstrate the degree of success attainable from the easy to use approximations. Also, for some cables, values obtained by these methods may be as good as those obtained by more exact methods in the practical case, where the coupling parameters are subject to change (due to cable stretching, twisting, bending, etc.) with every deployment of the cable.

Figure 22(b) lists the measured and computed peak currents for the eleven-conductor sample. The *dB* variation is computed from

[2] Janis Klebers, *Electromagnetic Pulse Coupling with Lossless Multiconductor Transmission Lines*, Harry Diamond Laboratories TR-1711 (June 1975).

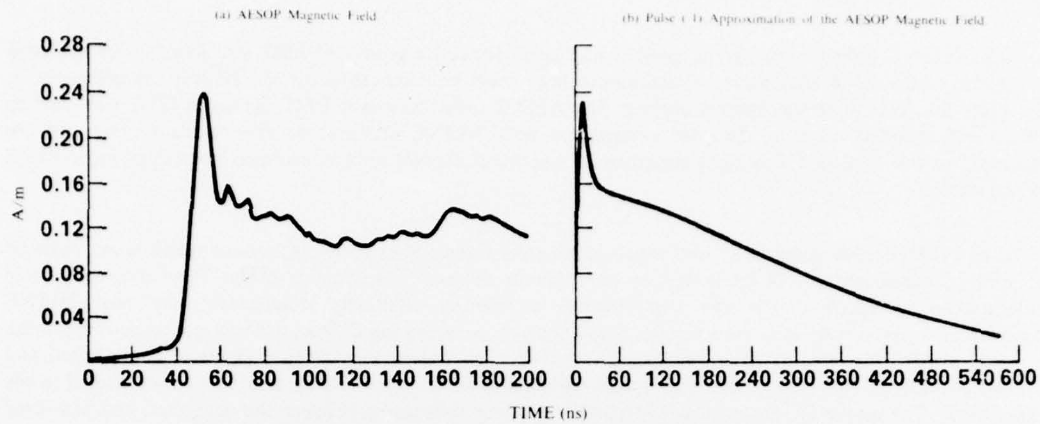


Figure 20. (a) Magnetic field measured in the AESOP simulator at 75 m on the center line. (b) Pulse(−1) approximation of the AESOP magnetic field used in the NLINE computations.

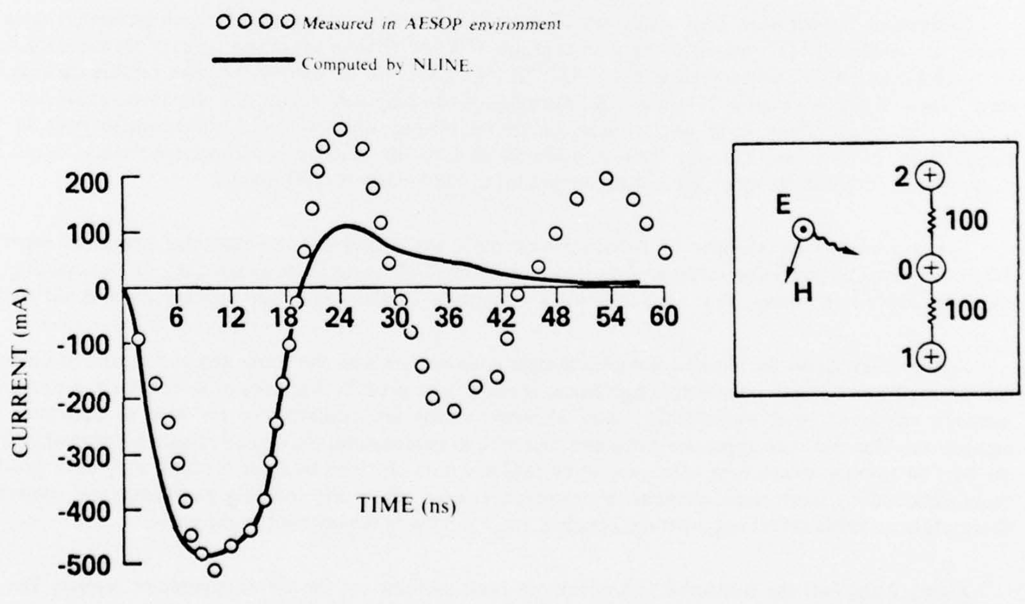
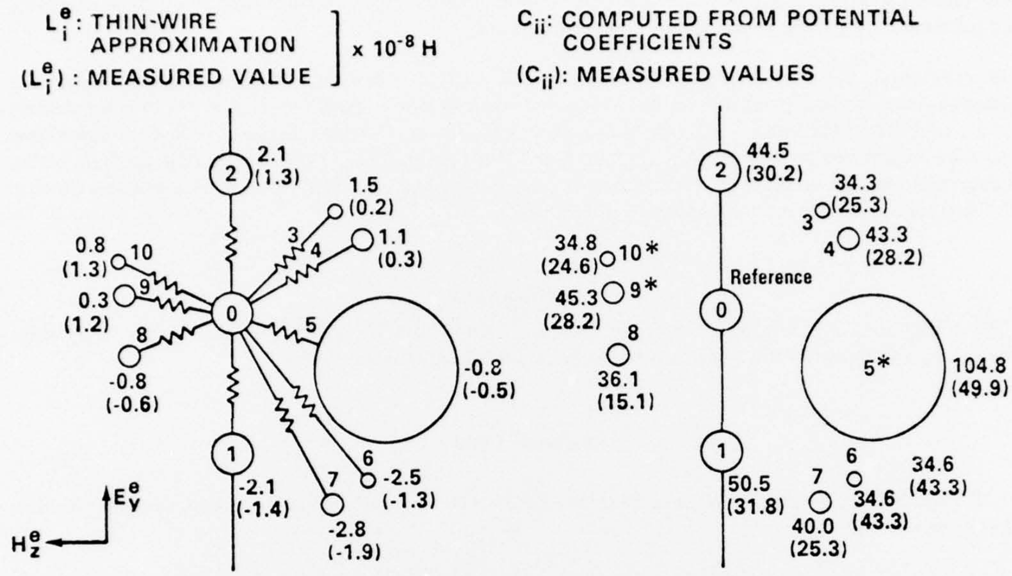


Figure 21. Comparison of the load current measured in the AESOP environment and the load current computed by NLINE for the three-conductor transmission line.



(a) Conductor geometry and cable-coupling parameters.

Conductor No.	Measured Peak Current in mA	Computed by NLINE	dB Variation
1	+500	+340	+ 3.35
2	-400	-475	- 1.49
3	-240	-205	+ 1.37
4	-140	-190	- 2.65
5	+280	+ 85*	+10.35
6	+280	+230	+ 1.71
7	+340	+330	+ 0.26
8	+240	+100	+ 7.60
9	+120	- 45*	*
10	+120	- 48*	*

(b) Peak induced currents: Measured and computed for the AESOP environment.

* Indicates large error introduced either in the measurement or computation of the coupling parameters.

Figure 22. Comparisons of measured and computed results for the eleven-conductor transmission line.

$$dB = 20 \log_{10}(\text{measured peak}/\text{computed peak}) . \tag{34}$$

It is evident from the table (fig. 22b) that the conditions for conductors 5, 9, and 10 were not adequately treated, either by the experiment, or by the computation. However, at least six conductors show relatively good agreement between the computed and measured results.

In conclusion, the application of the NLINE code to real cables requires use of good engineering judgement in order to obtain reliable results. Whenever possible, it is desirable to combine both computations and radiated EMP environment response measurements for the cable under analysis. A level of confidence can then be established for the NLINE computations. It is then possible to introduce circuit analysis codes, to change terminations or other NLINE input parameters, and use the NLINE code as a powerful tool in EMP vulnerability assessment and hardening programs.

Acknowledgements

The author thanks S. Frankel, J. N. Bombardt, R. F. Gray, and W. J. Stark for their helpful suggestions offered during the course of this work and L. Ambrose for his experimental work.

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2. J. Klebers, *Electromagnetic Pulse Coupling with Lossless Multiconductor Transmission Lines*, Harry Diamond Laboratories TR-1711 (June 1975).

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4. S. Ramo and J. R. Whinnery, *Fields and Waves in Modern Radio*, John Wiley and Sons, Inc., New York (1964).

5. G. Baker, A. McNutt, B. Shea, D. Rubenstein, *Damage Analysis Modified TRAC Computer Program (DAMTRAC)*, Harry Diamond Laboratories TM-75-6 (May 1975).

6. R. E. Collin, *Foundations for Microwave Engineering*, McGraw-Hill Book Company, New York (1966).

7. R. L. Hutchins, *Defense Nuclear Agency EMP Handbook*, BDM/A-135-75-TR-R1 (24 Sep 1975), Ch 14: EMP Data Analysis.

APPENDIX A. PROGRAM LISTING FOR THE CAPACITANCE AND MAGNETIC-FIELD COUPLING PARAMETER CODE, *PTNTL*

The determination of the capacitive and the inductive coupling parameters for multiconductor transmission lines has been defined and documented by many investigators, some of which are listed.[1,2,3,4,5] The methods for determining the parameters vary widely with respect to the degree of accuracy and the degree of difficulty in computation. Generally, all the methods are assumed to have the same degree of accuracy when the conductor spacings are large relative to the conductor radii, and the thin-wire conditions are approached. The thin-wire approximations appear to be adequate for some applications, and are desirable because of ease in computing the parameters.

The program in this section computes the Maxwell's capacitance coefficients from the potential coefficients, and computes the magnetic-field coupling parameters from the thin-wire approximation. The number of conductors, *N*, and the reference conductor, *IQ*, are designated by the user in the main deck as indicated by the "CU" comments. An 80-character FORTRAN comment COMNT is read in by

```
        READ(5,500)(COMNT(MN),MN=1,8)
500     FORMAT(8A10)
```

The cable-conductor cross-section coordinates are read into the program by

```
        READ(5,501)(R(NN),T(NN),NN=1,N)
501     FORMAT(8F10.3)
```

where R(NN),T(NN) are the r,θ polar coordinates of the centers of each conductor of the cable. The variable r is in meters and θ is in degrees. The angle θ is measured clockwise from the y-axis, as shown in figure 8, body of this report.

The conductor radii A(I) are given in meters and are specified by the user in the main deck. As an example, the coupling parameters for the Sample Problem were computed by PTNTL. The listing follows.

```
      PROGRAM PTNTL(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
CU    SUBROUTINES GELG, XIDENT, AND DELETX FROM NLINE MUST BE
C     ATTACHED TO THIS DECK.
C
C     THIS PROGRAM COMPUTES THE REDUCED MAXWELL"S CAPACITANCE MATRIX, AND THE
C     MAGNETIC FIELD COUPLING PARAMETERS FOR THE MULTICONDUCTOR TRANSMISSION
C     LINE.  THE CAPACITANCE MATRIX IS COMPUTED BY THE POTENTIAL COEFFICIENT
C     METHOD, AND THE MAGNETIC FIELD COUPLING PARAMETERS ARE COMPUTED FROM THE
C     THIN WIRE APPROXIMATION.
      DIMENSION RI(100),PI(121),PP(121)
      DIMENSION   P(11,11),X(11),Y(11),R(11),T(11),B(11,11),A(11),
     1COMNT(8)
      DATA C,RAD/1.8E10,.01745329/
CU    USER SETS EPR= TO EFFECTIVE VALUE OF THE RELATIVE DIELECTRIC
C     CONSTANT OF THE CABLE.
      EPR=1.
CU    USER SETS N= TO NUMBER OF CONDUCTORS IN THE CABLE.
      N=3
CU    USER SETS IQ= TO THE REFERENCE CONDUCTOR NUMBER.
      IQ=1
      KREF=IQ
CR    USER GENERATED COMMENT OF FORTRAN CHARACTERS READ IN FROM COLUMNS 1
C     THROUGH 80 ON DATA CARD.
      READ(5,500)(COMNT(MN),MN=1,8)
  500 FORMAT(8A10)
CR    COORDINATES OF THE CABLE CONDUCTOR CROSS SECTION ARE READ
C     HERE, IN POLAR FORM.
C     THETA IS MEASURED CLOCKWISE FROM THE Y-AXIS.
C     R IS IN METERS, AND THETA IS IN DEGREES.
```

---

[1] J. D. Clements and C. R. Paul, *Computation of the Capacitance Matrix for Dielectric-Coated Wires*, University of Kentucky, RADC-TR-74-89, Phase Report (March 1974).

[2] S. Frankel, *Cable and Multiconductor Transmission Line Analysis*, Harry Diamond Laboratories TR-091-1 (28 June 1974).

[3] K. Kajfez, *Multiconductor Transmission Lines*, Interaction Note I-51, Air Force Weapons Laboratory, Kirtland AFB, (June 1972).

[4] R. C. Keyser, *Modeling Techniques for Multiconductor Cables. Theory and Practice.* Air Force Weapons Laboratory AFWL-TR-72-89 (March 1973).

[5] S. Ramo and J. R. Whinnery, *Fields and Waves in Modern Radio*, John Wiley and Sons, Inc., 2nd ed., New York (1964), 263.

```
      READ(5,501)(R(NN),T(NN),NN=1,N)
501   FORMAT(8F10.3)
      EP=1.E-15
      DA=6.163E-02
      DAA=0.
      NP=N-1
CU    USER PROVIDES VALUES FOR A(I)=RADIUS OF THE I-TH CONDUCTOR,
C     FOR ALL CONDUCTORS IN THE TRANSMISSION LINE.
      A(1)=.083
      A(2)=.105
      A(3)=.105
      DO 11 J=1,N
      X(J)=R(J)*SIN(RAD*T(J))
   11 Y(J)=R(J)*COS(RAD*T(J))
      DO 12 I=1,N
      DO 12 J=1,N
      IF(I.EQ.J)GOTO13
      B(I,J)=SQRT((X(I)-X(J))**2+(Y(I)-Y(J))**2)
      GOTO12
   13 B(I,J)=A(J)
   12 CONTINUE
      DO 14 I=1,N
      DO 14 J=1,N
   14 P(I,J)=C*ALOG(B(I,KREF)*B(KREF,J)/B(I,J)/B(KREF,KREF))/EPR
      WRITE(6,599)(COMNT(MN),MN=1,8)
      WRITE(6,702)
  702 FORMAT(1H ,9X1HX,9X1HY/)
      DO 16 J=1,N
   16 WRITE(6,600)(X(J),Y(J))
      WRITE(6,703)
  703 FORMAT(1H0,22HPOTENTIAL COEFFICIENTS///)
      DO 15 I=1,N
   15 WRITE(6,601)(P(I,M),M=1,N)
  599 FORMAT(1H1,8A10///)
  600 FORMAT(1H ,2E14.4)
  601 FORMAT(1H ,1P11E12.3)
      CALL XIDENT(NP,RI)
      L=0
      DO 19 J=1,N
      DO 19 K=1,N
      L=L+1
   19 PI(L)=P(J,K)
      CALL DELETX(IQ,N,PI,PP)
      CALL GELG(RI,PP,NP,NP,EP,IER)
C     RI=CAPACITANCE MATRIX
      L=0
      DO 17 J=1,NP
      DO 17 K=1,NP
      L=L+1
   17 P(J,K)=RI(L)
      WRITE(6,701)IER,DAA
  701 FORMAT(1H-,4HIER=,I13,3X,1F6.2,5H*A(J)///)
      WRITE(6,700)
  700 FORMAT(1H-,18HCAPACITANCE MATRIX/)
      DO 18 I=1,NP
   18 WRITE(6,601)(P(I,M),M=1,NP)
      WRITE(6,800)
  800 FORMAT(1H0,78HMAGNETIC FIELD COUPLING PARAMETERS L(1),L(2),....,L(N
     1)  ,WITH REFERENCE L(IQ)=0//)
      DO 801 K8=1,N
      XL=1.256637E-6*(Y(K8)-Y(IQ))
  801 WRITE(6,802)XL
  802 FORMAT(1P1E17.7)
      STOP
      END
```

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