Sensor and Simulation Notes

Note 62

A Parameter Study of Open-Circuited and Short-Circuited Transmission Line Simulation for Buried Structures of EMP Sensor and Simulation Note XXII

by

Terry L. Brown

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The Dikewood Corporation
1009 Bradbury Drive, S. E.
University Research Park
Albuquerque, New Mexico 87106

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## CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>1</td>
</tr>
<tr>
<td>I - INTRODUCTION</td>
<td>2</td>
</tr>
<tr>
<td>II - OPERATION</td>
<td>4</td>
</tr>
<tr>
<td>General</td>
<td>4</td>
</tr>
<tr>
<td>Program EXAMN</td>
<td>7</td>
</tr>
<tr>
<td>GRAPHS</td>
<td>9</td>
</tr>
<tr>
<td>Appendix</td>
<td></td>
</tr>
<tr>
<td>A - FLOW CHARTS</td>
<td>31</td>
</tr>
<tr>
<td>B - PROGRAM LISTING</td>
<td>37</td>
</tr>
</tbody>
</table>
The magnitude of open-circuited and short-circuited transmission line impedances versus frequency are graphed for various values of the geometric factor, depth of the transmission line and ground conductivity. A computer code that produces the plots for any value of the parameters is described and listed.
1. INTRODUCTION

In this note the influence of three parameters on the frequency versus the magnitude of the impedance for a buried transmission line simulator is studied; the study is based on an analysis by Carl E. Baum.* The simulator consists of two parallel plates of width $2a$, separated by a distance of $2b$, and a depth into the ground of $\ell$. The geometry of the configuration is shown in Figure 1.

The limit of our concern in this note is to compare frequency to the impedance of the open-circuited and short-circuited transmission line for various plate-depths, ground conductivity and geometric factors. A computer code that can easily be used to produce graphs for any value of the parameters is included since not all interesting combinations can be presented here.
II. OPERATION

General

The plots contained in this note were produced on the Calcomp Plotter. Each graph is logarithmic vertically and logarithmic horizontally with 150 points plotted along each curve. The heading of each graph contains the three parameters, that is, plate depth (L), conductivity, and the geometric factor.

Practically, it is more desirable to describe the geometry of the simulator in terms of the ratio of the plate separation to the plate width (b/a) than in terms of the geometric factor ($f_g$). For this reason, provisions have been made to list b/a to clarify the geometry. However, it should be noted that $f_g$ and not b/a is necessary for the calculations in the program. The code does not calculate $f_g$ from b/a. If the geometric factor is not known for a given b/a it can be determined with the computer code described in EMP Sensor and Simulation Note LII.¹

The impedances for the two curves of each graph are given by equations (1) and (2), below. These values are computed and plotted for various combinations of the parameters. Since these quantities are generally complex, the magnitude of each is plotted against frequency. The frequency is in cycles per second. The curves are distinguished by tagging

them with $Z_{L_o}$ and $Z_{L_s}$ for the magnitude of the open-circuited and magnitude of the short-circuited transmission line impedance, respectively.

Accepting from Note XXII, along with their restrictions, we have

the open-circuited transmission line impedance

$$Z_{L_o} = \frac{Z_L}{Z_{L\infty}} \frac{1 + e^{-j2k\ell}}{1 - e^{-j2k\ell}}$$

(1)

and the short-circuited transmission line impedance

$$Z_{L_s} = \frac{Z_L}{Z_{L\infty}} \frac{1 - e^{-j2k\ell}}{1 + e^{-j2k\ell}}$$

(2)

The impedance of an infinite or ideal transmission line is given by

$$Z_{L\infty} = \frac{f}{g} \frac{1 + j}{\delta \sigma}$$

(3)

where the propagation constant, $k$, is

$$k \approx \frac{1 - j}{\delta}$$

(4)

and skin depth is

$$\delta \approx \sqrt{\frac{2}{\omega \mu \sigma}} = \sqrt{\frac{1}{\pi \ell \mu \sigma}}$$

(5)
A description of the variables is as follows:

<table>
<thead>
<tr>
<th>Variable</th>
<th>Designation</th>
<th>Unit of Measure</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu$</td>
<td>Ground permeability</td>
<td>$\mu = \mu_0 = 4\pi \times 10^{-7}$ henrys/meter</td>
</tr>
<tr>
<td>$f_g$</td>
<td>Geometric factor</td>
<td></td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Ground conductivity</td>
<td>mhos/meter</td>
</tr>
<tr>
<td>$k$</td>
<td>Propagation constant</td>
<td></td>
</tr>
<tr>
<td>$f$</td>
<td>Frequency</td>
<td>cycles/second</td>
</tr>
<tr>
<td>$\ell$</td>
<td>Plate depth</td>
<td>meters</td>
</tr>
<tr>
<td>$\delta$</td>
<td>Skin depth</td>
<td></td>
</tr>
</tbody>
</table>

The table below summarizes the graphs found in this note.

<table>
<thead>
<tr>
<th>$\frac{f}{g}$</th>
<th>$\frac{b}{a}$</th>
<th>$\ell$</th>
<th>$\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.47263359</td>
<td>1.0</td>
<td>20.0</td>
<td>$5.00 \times 10^{-3}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>20.0</td>
<td>$8.00 \times 10^{-3}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>20.0</td>
<td>$1.10 \times 10^{-2}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>20.0</td>
<td>$3.00 \times 10^{-2}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>40.0</td>
<td>$5.00 \times 10^{-3}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>40.0</td>
<td>$8.00 \times 10^{-3}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>40.0</td>
<td>$1.10 \times 10^{-2}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>40.0</td>
<td>$3.00 \times 10^{-2}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>60.0</td>
<td>$5.00 \times 10^{-3}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>60.0</td>
<td>$8.00 \times 10^{-3}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>60.0</td>
<td>$1.10 \times 10^{-2}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>60.0</td>
<td>$3.00 \times 10^{-2}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>80.0</td>
<td>$5.00 \times 10^{-3}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>80.0</td>
<td>$8.00 \times 10^{-3}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>80.0</td>
<td>$1.10 \times 10^{-2}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>80.0</td>
<td>$3.00 \times 10^{-2}$</td>
</tr>
<tr>
<td>$f_g$</td>
<td>1.0</td>
<td>-100.0</td>
<td>5.00 x 10^{-3}</td>
</tr>
<tr>
<td>----------</td>
<td>------</td>
<td>--------</td>
<td>----------------</td>
</tr>
<tr>
<td>100.0</td>
<td></td>
<td></td>
<td>8.00 x 10^{-3}</td>
</tr>
<tr>
<td>100.0</td>
<td></td>
<td></td>
<td>1.10 x 10^{-2}</td>
</tr>
<tr>
<td>100.0</td>
<td></td>
<td></td>
<td>3.00 x 10^{-2}</td>
</tr>
</tbody>
</table>

The following graphs were reproduced directly from the Calcomp plots.
MAGNITUDE OF OPEN-CIRCUITED AND SHORT-CIRCUITED TRANSMISSION LINE IMPEDANCE VERSUS FREQUENCY FOR
L = 20.0 METERS, CONDUCTIVITY = 5.00E-03 MH/CMETE
FG = .473 (B/A = 1.00)
MAGNITUDE OF OPEN-CIRCUITED AND SHORT-CIRCUITED TRANSMISSION LINE IMPEDANCE VERSUS FREQUENCY FOR
L = 20.0 METERS, CONDUCTIVITY = 8.00E-03 M\(\cdot\)H\(\cdot\)S/METER
FG = .473 (B/A = 1.00)
MAGNITUDE OF OPEN-CIRCUITED AND SHORT-CIRCUITED TRANSMISSION LINE IMPEDANCE VERSUS FREQUENCY FOR
L = 20.0 METERS, CONDUCTIVITY = 1.10E-02 MHOS/METER
FG = .473 (B/A = 1.00)
MACNITUDE OF OPEN-CIRCUITED AND SHORT CIRCUITED TRANSMISSION LINE IMPEDANCE VERSUS FREQUENCY FOR
L = 20.0 METERS, CONDUCTIVITY = 3.00E-02 MHOS/METER
FG = .473 (B/A = 1.00)
MAGNITUDE OF OPEN-CIRCUITED AND SHORT-CIRCUITED TRANSMISSION LINE IMPEDANCE VERSUS FREQUENCY FOR
L = 40.0 METERS, CONDUCTIVITY = 5.00E-03 MHOS/METER
FG = .473 (B/A = 1.00)
MAGNITUDE OF OPEN-CIRCUITED AND SHORT-CIRCUITED TRANSMISSION LINE IMPEDANCE VERSUS FREQUENCY FOR
L = 40.0 METERS, CONDUCTIVITY = 8.00E-03 MHOS/METER
FG = .473 (B/A = 1.00)
MAGNITUDE OF OPEN-CIRCUITED AND SHORT-CIRCUITED TRANSMISSION
LINE IMPEDANCE VERSUS FREQUENCY FOR
L = 40.0 METERS, CONDUCTIVITY = 1.10E-02 Mhos/Meter
F_0 = .473 (B/A = 1.00)
MAGNITUDE OF OPEN-CIRCUITED AND SHORT-CIRCUITED TRANSMISSION LINE IMPEDANCE VERSUS FREQUENCY FOR
L = 40.0 METERS, CONDUCTIVITY = 3.00E-02 MHOS/METER
FG = .473 (B/A = 1.00)
MAGNITUDE OF OPEN-CIRCUITED AND SHORT-CIRCUITED TRANSMISSION LINE IMPEDANCE VERSUS FREQUENCY FOR

$L = 60.0$ METERS, CONDUCTIVITY $= 5.00E-03$ MHYS/METER

$FG = .473$ ($B/A = 1.00$)
Magnitude of open-circuited and short-circuited transmission line impedance versus frequency for

\[ L = 60.0 \text{ meters}, \ \text{conductivity} = 8.00 \times 10^{-3} \text{ mhos/meter} \]

\[ \text{FG} = 0.473 \ (B/A = 1.00) \]
MAGNITUDE OF OPEN-CIRCUITED AND SHORT-CIRCUITED TRANSMISSION LINE IMPEDANCE VERSUS FREQUENCY FOR
L = 60.0 METERS, CONDUCTIVITY = 1.10E-02 MHOS/METER
FG = .473 (B/A = 1.00)
MAGNITUDE OF OPEN-CIRCUITED AND SHORT-CIRCUITED TRANSMISSION LINE IMPEDANCE VERSUS FREQUENCY FOR
L = 60.0 METERS, CONDUCTIVITY = 3.00E-02 MHOS/METER
FG = .473 (B/A = 1.00)

![Diagram showing magnitude of impedance vs. frequency.
The graph plots |Z_L0| and |Z_Ls| against frequency (CPS).
|Z_L0| remains constant, while |Z_Ls| increases with frequency.

-19-
MAGNITUDE OF OPEN-CIRCUITED AND SHORT-CIRCUITED TRANSMISSION LINE IMPEDANCE VERSUS FREQUENCY FOR
L = 80.0 METERS, CONDUCTIVITY = 5.00E-03 MHES/STER
FG = .473 (B/A = 1.00)
MAGNITUDE OF OPEN CIRCUITED AND SHORT-CIRCUITED TRANSMISSION LINE IMPEDANCE VERSUS FREQUENCY FOR
L = 80.0 METERS, CONDUCTIVITY = 8.00E-03 MHØS/METER
FG = .473 (B/A = 1.00)
MAGNITUDE OF OPEN-CIRCUITED AND SHORT-CIRCUITED TRANSMISSION LINE IMPEDANCE VERSUS FREQUENCY FOR
L = 80.0 METERS, CONDUCTIVITY = 1.10E-02 MHØS/METER
FG = .473 (B/A = 1.00)
MAGNITUDE OF OPEN-CIRCUITED AND SHORT-CIRCUITED TRANSMISSION LINE IMPEDANCE VERSUS FREQUENCY FOR

L = 80.0 METERS, CONDUCTIVITY = 3.00E-02 MH/MS/METER

FG = .473 (B/A = 1.00)
MAGNITUDE OF OPEN-CIRCUITED AND SHORT-CIRCUITED TRANSMISSION LINE IMPEDANCE VERSUS FREQUENCY FOR
L = 100.0 METERS, CONDUCTIVITY = 5.00E-03 Mhos/METER
FG = .473 (B/A = 1.00)
MAGNITUDE OF OPEN-CIRCUITED AND SHORT-CIRCUITED TRANSMISSION LINE IMPEDANCE VERSUS FREQUENCY FOR

\( L = 100.0 \) METERS, CONDUCTIVITY = 8.00E-03 MHOS/METER

\( \phi_G = 0.473 \) (B/A = 1.00)
MAGNITUDE OF OPEN-CIRCUITED AND SHORT-CIRCUITED TRANSMISSION LINE IMPEDANCE VERSUS FREQUENCY FOR
L = 100.0 METERS, CONDUCTIVITY = 1.10E-02 Mhos/Meter
FG = .473 (B/A = 1.00)
MAGNITUDE OF OPEN-CIRCUITED AND SHORT-CIRCUITED TRANSMISSION LINE IMPEDANCE VERSUS FREQUENCY FOR

L = 100.0 METERS, CONDUCTIVITY = 3.00E-02 MHΩS/METER

FG = .473 (B/A = 1.00)
**Program EXAMN**

Program EXAMN accepts parameters from data cards as follows:

<table>
<thead>
<tr>
<th>Variable Name</th>
<th>Column</th>
<th>Type</th>
<th>Format by Which Variable is Read</th>
<th>Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>STOPRD</td>
<td>1</td>
<td>Alpha-numeric</td>
<td>1A1</td>
<td>Stops reading cycle</td>
</tr>
<tr>
<td>FG</td>
<td>2-8</td>
<td>Real</td>
<td>F9.8</td>
<td>Geometric factor</td>
</tr>
<tr>
<td>BA</td>
<td>10-15</td>
<td>Real</td>
<td>F5.2</td>
<td>Ratio of the distance between the plates to the plate length (for clarification only)</td>
</tr>
<tr>
<td>L</td>
<td>20-25</td>
<td>Real</td>
<td>F7.2</td>
<td>Depth of the plate into the ground</td>
</tr>
<tr>
<td>SIGMA</td>
<td>30-35</td>
<td>Real</td>
<td>E9.2</td>
<td>Conductivity of ground</td>
</tr>
</tbody>
</table>

The program generates one graph for each data card that it reads except the last data card which should contain an asterisk (*) in the first column to stop the reading cycle. The graphs drawn by EXAMN are logarithmic vertically and horizontally. The plots measure six inches by six inches.

The domain of the frequency consists of three consecutive decades between $10^2$ and $10^7$. The program determines this domain in order to calculate values of $\left| Z_{L_0} \right|$ and $\left| Z_{L_s} \right|$ in an area of interest. The range, $R$, of $\left| Z_{L_0} \right|$ and $\left| Z_{L_s} \right|$ is $10^{-1} \leq R \leq 10^2$ unless $Z_{L_s} = f(F(1))$ is less than $10^{-1}$ in which case the range is shifted so that $10^{-2} \leq R \leq 10^1$.

The program generates approximately 50 values of the frequency for each of the three decades and calculates corresponding values for $\left| Z_{L_0} \right|$ and
The numbers are listed by the printer along with the parameters that determine them.

Subroutine ADJUST is called in the event values of $|Z_L|$ and $|Z_L|$ fall beyond the upper limit of the range for the selected domain. This routine adjusts the data to the extent of retaining only those points within the upper limits of the graph. The adjusted points are then plotted.

Output to the Calcomp Plotter consists of, for each data card, a log-log graph of $f$ versus $Z_L$ and $f$ versus $Z_L$ along with a heading listing the three parameters. Differentiating tags are positioned at the tenth point plotted for each curve.

One one-half inch plot tape is required by Program EXAMN. The Calcomp Plotter instructions are written on this tape and it must be specified as a low density tape (200 BPI). The logical designation for this tape is 10 and must appear as such in the control cards.

CPU time to compile and produce the first graph is approximately 27 seconds. Each subsequent graph takes less than five seconds. The program will compile and execute in a field of $(53000)^8$. These figures are based on the use of the CDC Chippewa Fortran System on a CDC 6600 computer.
Appendix A

Flow Charts for Program EXAMN
START

\[ \pi, \mu_0 \]  
\[ \text{MUZER} = \mu_0 \]  
\[ \text{DELTAP} = 5.0 \]  
\[ \text{PIMU} = \pi \mu_0 \]

Read STOPRD, FG SIGMA, BA, L

Is STOPRD=*?  
Yes END

No

Write Heading and Sub-Heading

\[ \text{DEOM} = L^*L^*PIMU*SIGMA \]  
\[ A = 1/(\text{DEOM}^*\text{DELTAP}^*\text{DELTAP}) \]

1

1

Is \( A \leq 5000 \)?  
Yes  \( F(1) = 100 \)

No

Is \( A > 5000 \)?  
Yes  \( F(1) = 1000 \)

No

Is \( A > 50000 \)?  
Yes  \( F(1) = 10000 \)

No

Is \( A > 500000 \)?  
Yes  \( F(1) = 100000 \)

No

II = 50

2
$$F(II) = 10^{**}$$
$$(II/50) \times F(1)$$
$$II = II + 50$$

Is $II = 150$?

Yes

$$FINV1 = (F(50) - F(1))/50$$
$$FINTV2 = (F(100) - F(50))/50$$
$$FINTV3 = (F(150) - F(100))/50$$

$M = 2$

Is $M \geq 50$?

Yes

$$F(M) = FINTV1 + F(M-1)$$

No

Is $M = 149$?

Yes

$3$
\[ \delta = \sqrt{1/\pi \mu_0 F(N) \sigma} \]

\[ Z_{L_n} = \frac{1 + j}{\delta \sigma} \]

\[ Z_{L_0} = Z_{L_n} \frac{1 + e^{-j2k\ell}}{1 - e^{-j2k\ell}} \]

\[ Z_{L_s} = Z_{L_n} \frac{1 - e^{-j2k\ell}}{1 + e^{-j2k\ell}} \]

\[ ZLOM(N) = Z_{L_0} \]
\[ ZLSM(N) = Z_{L_s} \]

Is \( N = 150 \) ?

Write
\[ ZLSM(N) \]
\[ ZLOM(N) \]
\[ F(N) \]

STARTH = \( F(1) \)
STARTV = 0.1
NODECH = 3
NODECV = 3
DECLNH = 2
DECLNV = 2
NPTS = 150, KIND = 3,
LAST = -1, YMAX =
STARTV * 10 ** NODECV,
MORE = 155, COX =
F(150)

CALL ADJUST
Is \( ZLOM(150) > YMAX \) ?

CALL DRAW

N = N + 1
STARTH = F(1)
NODECH = 3
NODECV = 3
DECLNH = 2
DECLNV = 2
NPTS = 150
KIND = 4
LAST = 1

CALL ADJUST

CALL DRAW

4

Is LOM(150) > YMAX?

5

Yes

No
GOL(N) = log 0, log 1, log 2, ..., log 10
Fill XARRAY and YARRAY with values to be graphed

BEGINNING A NEW GRAPH?

Overlay?

Write error message

CALL EXIT

RETURN

Initialize Plots

Center graph on 10 inch paper

Find (1,1) or closest point to (1,1) on graph

Draw axes, tic marks
Calculate and locate decade values. Terminate at (1,1) or closest point to (1,1) on graph.

N = 1

Scale and plot XARRAY (N) against YARRAY(N)

N = N+1

Is N = 10?
Appendix B

Program Listing
A three parameter study of sensor and simulation note 22

The open-circuited and short-circuited transmission line simulation for buried structures is examined.

This program reads the geometric factor, depth of transmission line, and ground conductivity, and returns graphs of frequency versus magnitude of the impedance.

**Program: Examine Input, Output, Tape 5 = Input, Tape 6 = Output, Tape 10**

*Parameter Definitions*

- **C**
  - `C PROGRAM EXAMN(INPUT,OUTPUT,TAP5=INPUT,TAP6=OUTPUT,TAPF10)`: Program declaration.
  - `C*******************************************************************`: Comment line.
  - `C A THREE PARAMETER STUDY OF`: Program title.
  - `CSENSOR AND SIMULATION NOTE 22`: Note reference.
  - `CTHE OPEN-CIRCUITED AND SHORT-CIRCUITED TRANSMISSION LINE`: Transmission line analysis.
  - `CSIMULATION FOR BURIED STRUCTURES IS EXAMINED.`: Simulation purpose.
  - `CTHIS PROGRAM READS THE GEOMETRIC FACTOR,`: Programs input parameters.
  - `CDEPTH OF TRANSMISSION LINE, AND GROUND CONDUCTIVITY,`: Additional input parameters.
  - `CAND RETURNS GRAPHS OF FREQUENCY VERSUS`: Output graphs.
  - `CMAGNITUDE OF THE IMPEDANCE.`: Output magnitude.

**Complex Variables**

- `REAL MUZER0,L`:
  - `REAL MUZER0,L`: Real variables.
- `DIMENSION F(200), ZLOM(200), ZLSM(200), XF(200), YF(200)`:
  - `DIMENSION F(200), ZLOM(200), ZLSM(200), XF(200), YF(200)`: Dimension declaration.
- `PI=3.14159265358979`:
  - `PI=3.14159265358979`: Constant.
- `MUZER0=.0000012566370614391`:
  - `MUZER0=.0000012566370614391`: Constant.
- `DELTA=1.0`:
  - `DELTA=1.0`: Constant.

**Variables and Formulas**

- `C=CPLX(1.0,1.0)`: Complex variable initialization.
- `READ (5,10) STOP,F1,F2,F3,F4,F5,F6,F7,F8,F9,F10`: Data reading.
- `IF (STOP.EQ.STAR1) GO TO 105`: Conditional statement.

**Program Flow**

- `WRITE (6,9) L,SIGMA,F1,RA`:
  - `WRITE (6,9) L,SIGMA,F1,RA`: Output statement.
- `FORMAT (1H1,30X,60HMAGNITUDE OF OPEN-CIRCUITED AND SHORT-CIRCUITED EX TRANSMISSION LINE IMPEDANCE VERSUS FREQUENCY FOR 30X,13HPL`:
  - `FORMAT (1H1,30X,60HMAGNITUDE OF OPEN-CIRCUITED AND SHORT-CIRCUITED EX TRANSMISSION LINE IMPEDANCE VERSUS FREQUENCY FOR 30X,13HPL`: Output format.
- `WRITE (6,20) F(1),F(2),F(3),F(4),F(5),F(6),F(7),F(8),F(9),F(10)`: Output data.

**Mathematical Formulas**

- `A=1.0/(DENM*DELTA*DELTA)`:
  - `A=1.0/(DENM*DELTA*DELTA)`: Formula calculation.
- `IF(A.EQ.5000.0)F(I)=100.`:
  - `IF(A.EQ.5000.0)F(I)=100.`: Conditional formula.
- `IF(A.GT.5000.0)F(I)=1000.`:
  - `IF(A.GT.5000.0)F(I)=1000.`: Conditional formula.
- `IF(A.GT.50000.0)F(I)=10000.`:
  - `IF(A.GT.50000.0)F(I)=10000.`: Conditional formula.
- `IF(A.GT.500000.0)F(I)=100000.`:
  - `IF(A.GT.500000.0)F(I)=100000.`: Conditional formula.

**Output Data**

- `DO 40 I=50,150,50`: Loop initialization.
- `F(I)=10**(I/50)*F(1)`:
  - `F(I)=10**(I/50)*F(1)`: Formula calculation.
- `FINTV1=(F(50)-F(1))/50.`:
  - `FINTV1=(F(50)-F(1))/50.`: Integral calculation.
- `FINTV2=(F(100)-F(50))/50.`:
  - `FINTV2=(F(100)-F(50))/50.`: Integral calculation.
- `FINTV3=(F(150)-F(100))/50.`:
  - `FINTV3=(F(150)-F(100))/50.`: Integral calculation.
45  F(M)=F(NTV1+F(M-1))          FX 15
46  GO TO 45                       FX 16
50  IF (M=100) .55,65,60           FX 27
55  F(M)=F(NTV2+F(M-1))           FX 38
60  GO TO 65                       EX 39
65  F(M)=F(NTV3+F(M-1))           FX 40
CONTINUE                        EX 41
70  ON 70 N=1,150                  EX 42
DELTA=SQR(1.0/(PI*M*M(N)*SIGMA)) EX 43
ZI=DELTA*G1/(DELTA*SIGMA)        EX 44
B=LN(-2.0/DELTA)                  EX 45
C=CMPLX(B,B)                      EX 46
ETOX=EXP(C)                       EX 47
ZLO=ZI*AL*LN1.0+ETOX)/(1.0-ETOX)  EX 48
ZLOM(N)=CARS(ZLO)                 EX 49
ZLS=ZI*AL*LN1.0-ETOX)/(1.0+ETOX)  EX 50
ZLSM(N)=CARS(ZLS)                 EX 51
CONTINUE                        EX 52
75  WRITE (6,75) (FN(N),ZLOM(N),ZLSM(N),F(N+100),ZLOM(N+100),ZLSM(N+100),NN=1,50) EX 53
IN+50),F(N+100),ZLOM(N+100),ZLSM(N+100),NN=1,50) EX 54
80  FORMAT (1X,3F10.2,1X,3F10.2,3E10.2) FX 55
   STARTH=F(1)                     FX 56
   IF(ZLSM(1).LT.1) STARTV=.01     FX 57
   IF(ZLSM(1)).GT.1) STARTV=.1     FX 58
   NODECH=3                        FX 59
   NODECV=3                        FX 60
   DECLNH=2                        FX 61
   DECLNV=2                        FX 62
   NPTS=150                       FX 63
   KIND=3                         EX 64
   LAST=-1                        EX 65
   YMAX=STARTV*10.0**(NOCVCV)     EX 66
   MORE=155                        EX 67
   COX=F(150)                      EX 68
   IF(ZLOM(150).GT.YMAX) GO TO 80  EX 69
   GO TO 85                        EX 70
85  CALL ADJUST(1,F,ZLOM,NPTS,COX,YMAX,XY,DF,MORE,NEWPTN) FX 71
   CALL DRAWL(STARTH,STARTV,NODECH,NODECV,DECLNH,DECLNV,NEWPTN,XY, LYT,KIND,LAST,BACK) FX 72
   GO TO 80                       FX 73
GO TO 90                         FX 74
90  CALL DRAWL (STARTH,STARTV,NODECH,NODECV,DECLNH,DECLNV,NPTS,F,7LOM, KIND,LAST,BACK) FX 75
   STARTH=F(1)                    RX 76
   NODECH=3                       EX 77
   NODECV=3                       EX 78
   DECLNH=2                       FX 79
   DECLNV=2                       EX 80
   NPTS=150                      EX 81
   KIND=4                         EX 82
-38-
LAST=1
IF(7LDM(I50).GT.YMAX) GO TO 95
CALL DRAWL(STARTH,STARTV,NODECH,NODECV,DECLNH,DECLNV,NPTS,F,ZLSM,EX,84)
1KIND,LAST,BACK)
GO TO 100
95 CALL ADJUST(F,ZLSM,NPTS,COX,YMAX,XF,YF,MORE,NEWPTS)
CALL DRAWL(STARTH,STARTV,NODECH,NODECV,DECLNH,DECLNV,NEWPTS,XF,EX,89)
LYF,KIND,LAST,BACK)
100 CALL HEAD(6e,6e,L,SIGMA,FG,BACK)
GO TO 5
105 CONTINUEF
END
SUBROUTINE DRAWL (STARTH,STARTV,NODECH,NODECV,DECLNH,DECLNV,NPTS,X TL
 IARRAY,YARRAY,KIND,LAST,XT)
 **********************************************************************
 C     THIS SUBROUTINE SCALDS. DRAWS THE AXIS FOR THE LOG LOG GRAPH, AND
 C     PLOTS THE DATA WITH ANY NUMBER OF OVERLAYS ON THE CALCOMP PLOTTER.
 C
 C**********************************************************************
 DIMENSION X(200), Y(200), GOL(11), XARRAY(NPTS), YARRAY(NPTS)
 DATA GOL/0,0,17609,30103,47712,60206,69897,77815,84510,903/ TL
 10999427,1.9,1F/2H/2/,COREFY/C/,CORECX/C/,JFT/2H1/
 00 5 I=1,NPTS TL
X(I)=XARRAY(I) TL
5 Y(I)=YARRAY(I)
I=0K=KIND TL
10 IF (KIND-3) 15,25,10
15 IF (KIND-4) 15,150,15
20 WRITE (6,20) KIND
10 FORMAT (41H THE KIND OF GRAPH ASKED FOR IS IN ERROR,1B) TL
 RETURN
25 IF (IN-2) 30,35,30
30 CALL PLOTS (TB,TB,19) TL
35 IN=2 TL
 REALH=RNODEC+DECLNV
 YS=(10.-REALH)/2.-5 TL
 CALL PLOT (N.,YS,-3)
 GO TO 85
35 K=0 TL
 GO TO (40,45,50,55,60,65,70,75,80,K) K
40 CALL FIND1 (STARTH,NODECH,DECLNH,XXX) TL
 CALL FIND1 (STARTV,NODECV,DECLNV,YYY)
 GO TO 85
45 CALL TOSMAL (STARTV,NODECV,COREFY,YYY,DECLNV) TL
 CALL FIND1 (STARTV,NODECV,DECLNH,XXX) TL
 GO TO 85
50 CALL TOSMAL (STARTV,NODECV,CORECX,YYY,DECLNV) TL
 CALL FIND1 (STARTV,NODECV,DECLNH,XXX)
 GO TO 85
55 CALL TOSMAL (STARTH,NODECH,CORECX,XXX,DECLNH)
 CALL FIND1 (STARTV,NODECV,DECLNV,YYY)
 GO TO 85
60 CALL TOSMAL (STARTH,NODECH,CORECX,XXX,DECLNH)
 CALL FIND1 (STARTV,NODECV,DECLFY,YYY)
 GO TO 85
65 CALL TOSMAL (STARTV,NODECV,CORECX,XXX,DECLNH)
 CALL TOLARG (STARTV,NODECV,COREFY,YYY)
 GO TO 85
70 CALL TOALARG (STARTV,NODECV,COREFX,XXX,DECLNH) TL
GO TO 85
70 CALL TOLARG (STARTH, NODECH, CORECX, XXX)
CALL FIND1 (STARTV, NODECV, DECLNV, YYY)
GO TO 85
75 CALL TOLARG (STARTH, NODECH, CORECX, XXX)
CALL TOSMAL (STARTV, NODECV, CORECY, YYY, DECLNV)
GO TO 85
80 CALL TOLARG (STARTH, NODECH, CORECX, XXX)
CALL TOLARG (STARTV, NODECV, CORECY, YYY)
85 NODECH=NODECH+1
NODECV=NODECV+1
XX=0.
POWEX=ALOG10(STARTH)
ILOG=POWEX+SIGN(.000001,POWEX)
DO 100 I=1,NODECH
REAL(i)=I-1
INUM=ILOG+(I-1)
RR=XX-.12
RER=XX+.13
CALL SYMBOL (RR, -.3, 14, 2H10, 0, 2)
IF (INUM.GE.0.AND.INUM.LT.10) CALL NUMBER (RER, -.21, 10, INUM, 0., JF)
IT)
IF (INUM.LT.0.OR.INUM.GE.10) CALL NUMBER (RER, -.21, 10, INUM, 0., IFT
1)
CALL PLOT (XX, 0., 3)
IF (I-NODECH) 90, 105, 90
90 DO 95 J=1,11
XX=(GOL(J)+RFALI)*DECLNH
CALL PLOT (XX, 0., 2)
CALL PLOT (XX, -.05, 2)
95 CALL PLOT (XX, 0., 2)
100 CONTINUE
105 CONTINUE
NODEC=NODECV-1
DO 115 I=1,NODEC
REAL(i)=I-1
DO 110 J=1,11
YY=(GOL(J)+REALJ)*DECLNY
CALL PLOT (XX, YY, 2)
W=XX+.05
CALL PLOT (W, YY, 2)
110 CALL PLOT (XX, YY, 2)
115 CONTINUE
NODEC=NODECH-1
DO 125 I=1,NODEC
RELDEC=NODECH-1
DO 120 J=1,11
XX=DECLNH*(RELDEC-(1.0-GOL(-J+12)))
CALL PLOT (XX, YY, 2)
GO TO 210

195 N=0
200 IF(Y(I).LE.10.) GO TO 205
   Y(I)=Y(I)/10.
   N=N+1
   GO TO 200
205 REALN=N
   YY=(ALOG10(Y(I))REALN+COREC)*DECLNV
210 IF(I-1).GT.220,215,220
215 CALL PLOT(XX,YY,1)
   CALL PLOT(XX,YY,-1)
   GO TO 225
220 CALL PLOT(XX,YY,2)
   IF(I.EQ.10.AND.IMBOKK.EQ.3) CALL TAG(XX,YY,1)
   IF(I.EQ.10.AND.IMBOKK.EQ.4) CALL TAG(XX,YY,-1)
225 CONTINUE
   IF(LAST).GT.235,230,230
230 RNODEC=NODECH
   XT=XXX+RNODEC*DECLNH+3.
   CALL PLOT(XT,-YYY,-3)
235 RETURN
   END
SUBROUTINE FIND1 (START, NDEC, DECLN, XY)

C**************************************************************************************************C
C THIS SUBROUTINE LOCATES 1 ON THE VERTICAL OR HORIZONTAL AXIS.
C**************************************************************************************************

STARR=START
DO 15 I=1, NDEC
N=1
IF (ABS(STARR-1.0)-1.0E-6) 20,20, 5
5 IF (STARR-1.00) 10,20,20
10 STARP=STARR*10.
15 CONTINUE
20 REALN=N-1
XY=REALN*DECLN
RETURN
END
SUBROUTINE TOSMAL (START, NODEC, CORECS, XY, DECLN)  
C******************************************************************************
C   TO SMAL DETERMINES THE NUMBER OF DECADES DIFFERENCE BETWEEN 1 AND
C   THE LARGEST VALUE LESS THAN 1.
C******************************************************************************
CORECS=0.0  
XYMAX=START*10.0**NODEC  
RELNOD=NODEC  
XY=RELNOD*DECLN  
5 IF (ABS(XYMIN-1.0)-1.0E-6) 20,20,10  
10 IF (XYMAX-1.00) 15,20,20  
15 CORECS=CORECS+1.  
   XYMAX=XYMAX*10.  
   GO TO 5  
20 RETURN  
END
SUBROUTINE TOLARG (START,NODEC,CORECL,XY)

********************************************************************************
C
C TOLARG DETERMINES THE NUMBER OF DECADES DIFFERENCE BETWEEN 1 AND
C THE SMALLEST VALUE GREATER THAN 1.

********************************************************************************
XY=0.
CORECL=0.0
XYMIN=START
5 IF (ABS(XYMIN-1.0)-1.0E-6) 20,20,15
10 IF (XYMIN-1.0) 20,20,15
15 CORECL=CORECL-1.0
XYMIN=XYMIN+.1
GO TO 5
20 RETURN
END


SUBROUTINE FLAG (K, SHV, NODEC)

C******************************************************************
C SUBROUTINE FLAG determines what combination of subroutines
C 'FIND1, TOLARG, and TOSMAL should be called.
C******************************************************************

IF (ABS(SHV-1.)-1.0E-6) 25,25,5  
5 IF (SHV-1.00) 10,25,30  
10 ZHVT=SHV*10.**NODEC  
15 IF (ABS(ZHVT-1.0)-1.0E-6) 20,20,15  
20 K=K+2  
25 RETURN  
30 RETURN  
END
**SUBROUTINE HEAD (GL, GH, LG, SIGMA, FG, BA, BACK)**

```
CALL PLOT (-BACK, 0., -3)
GL02 = GL/2.
X1 = GL02 - 3.6
X2 = GL02 - 2.16
X3 = GL02 - 1.06
X4 = GL02 - 0.9
Y1 = GH + L / 6
Y2 = GH + 7.8
Y3 = GH + 5.4
Y4 = GH + 7.7
Y5 = -5

CALL SYMBOL (X1, Y1, 14, 60HMAGNITUDE OF OPEN-CIRCUITED AND SHORT-CI
RCUITED TRANSMISSION, 0., 30)
CALL SYMBOL (X2, Y2, 14, 35HLINE IMPEDANCE VERSUS FREQUENCY FOR, 0., 3)

CALL SYMBOL (X3, Y3, 14, 51HL = MEASUREMENTS, CONDUCTIVITY = 1
MHOS/METER, 0., 51)

CALL SYMBOL (X4, Y4, 14, 22HFG = (B/A = ), 0., 22)
CALL SYMBOL (X5, Y5, 14, 15HIMPEDANCE VS FREQUENCY (CPS), 0., 15)

XN1 = X4 + 1.6
XN2 = X3 + 1.7
XN3 = X4 + 3.8
XN4 = X4 + 2.04

CALL NUMBER (XN1, Y3, 14, L, 0., 4HFG, 1)
CALL NUMBER (XN2, Y3, 14, SIGMA, 0., 4HFG, 2)
CALL NUMBER (XN3, Y4, 14, FG, 0., 4HFG, 3)
CALL NUMBER (XN4, Y4, 14, BA, 0., 4HFG, 4)

Y6 = (GH - 1.75) / 2e + 0.1

CALL SYMBOL (-80, Y6, 14, 12HZ AND Z, 90., 12)
XS1 = -7
YS1 = Y6 + 12
DO 5 I = 1, 7
5 YS1 = YS1 + 1.37
XS2 = -80 + 15
YS2 = Y6 + 2.3

CALL SYMBOL (XS1, YS1, 14, 14HL, 90., 1)
YS1 = YS1 + 1.37
XS2 = -80 + 15
YS2 = Y6 + 2.3

CALL SYMBOL (XS2, YS2, 14, 110HZ, 90., 1)
YS2 = YS2 + 1.37
CALL SYMBOL (XS2, YS2, 14, 110HZ, 90., 1)
DO 15 T = 1, 2

ABSTRACT = Y6 + 0.5
```

-48-
DO 10 J=1,2
CALL PLOT (-.95,ABSIGN,3)
CALL PLOT (-.65,ABSIGN,2)
10 ABSIGN=ABSIGN+.4
15 Y6=Y6+1.32
CALL PLOT (BACK,0.,-3)
RETURN
END
SUBROUTINE TAG (X, Y, ISCP1)

* ALL PLOT (X, Y, 3)
* = (ISCP1) 15, 5, 20
* "ITC (6, 10)
* BMAT (10X, 33HARGUMENT ERROR IN SUBROUTINE TAG.)
* ALL EXIT

15 X=X+.1
Y=Y-.04
ALL PLOT (XX, YY, 2)
Y=Y+.04
ALL PLOT (XX, YY, 3)
Y=Y+.2
ALL PLOT (XX, YY, 2)
Y=Y-.07
1 TO 25
X=X+.04
Y=Y+.1
ALL PLOT (XX, YY, 2)
X=X-.04
ALL PLOT (XX, YY, 3)
ALL PLOT (X, Y, 2)
Y=Y+.4
ALL PLOT (X, Y, 2)
Y=Y-.06
Z=Y+.55

25 ALL SYMBOL (XZ, Y7+, 14, 1HZ, 001)
L=X7+.12
L=Y7-.1
ALL SYMBOL (XL, YL, 14, 1HL, 001)
NS=X7+.23
NS=Y7-.15
P = "SCRT) 30,5, 35
ALL SYMBOL (XOS, YOS, 07, 1HS, 001)
D TO 40
ALL SYMBOL (XOS, YOS, 07, 1HO, 001)

40 X=X7-.1
Y=Y7-.15
ALL PLOT (XX, YY, 3)
Y=YY+.35
ALL PLOT (XX, YY, 2)
X=XZ+.35
ALL PLOT (XX, YY, 3)
YY = YY - .35
CALL PLOT (XX, YY, 2)
CALL PLOT (X, Y, 3)
RETURN
END
SUBROUTINE ADJUST(X,Y,NPTS,XM,YM,XF,YF,MORE,L)  
*****************************************************************************  
*  
*  THIS SUBROUTINE ADJUSTS ALL DATA POINTS IN THE FIRST QUADRANT THAT  
*  OVERFLOW THE GIVEN LIMITS OF THE BOUNDARY TO THE BOUNDARY WITHOUT THE  
*  LOSS OF THE SLOPE FROM THE INTERIOR POINT TO THE EXTERIOR POINT  
*  
*****************************************************************************  
  
DIMENSION X(NPTS), Y(NPTS), XF(MORE), YF(MORE)  
L=0  
I=0  
I=I+1  
IF (I-NPTS) LE 15,35,45  
10  
   K=0  
   IF (X(I).GT.XM.AND.X(I+1).GT.XM) GO TO 5  
   IF (Y(I).GT.YM.AND.Y(I+1).GT.YM) GO TO 5  
   IF (X(I).GT.XM.OR.X(I+1).GT.XM) K=1  
   IF (Y(I).GT.YM.OR.Y(I+1).GT.YM) K=K+2  
   IF (K.LE.15) GO TO 15  
15  
   C=X(I)  
   D=Y(I)  
   E=X(I+1)  
   F=Y(I+1)  
   CALL EDGE (C,D,E,F,K,KK,XM,YM)  
   IF (KK) 5,20,19  
   L=L+1  
20  
   GO TO (25,30,31), KK  
25  
   XF(L)=C  
   YF(L)=D  
   GO TO 5  
30  
   XF(L)=C  
   YF(L)=D  
   L=L+1  
   XF(L)=E  
   YF(L)=F  
   GO TO 5  
35  
   IF (X(I).LE.XM.AND.Y(I).LE.YM) GO TO 40  
   GO TO 45  
40  
   L=L+1  
   XF(L)=X(I)  
   YF(L)=Y(I)  
   GO TO 5  
45  
   RETURN  
FIN
SUBROUTINE FDGE (XI, YI, X2, Y2, K, KK, XM, YM)  
* SUBROUTINE FDGE CALCULATES THE INTERSECTION OF THE LINE ADJOINING  
* TWO POINTS AND THE LINES X=XM, Y=YM OR BOTH  
******************************************************************************

IF (XI-X2) .LE. 95.5
  SLOPE=(Y2-Y1)/(X2-X1)
  B=Y1-SLOPE*X1
  M=1
  GO TO (15, 55, 80), K
15 IF (X2-X1) .GE. 25, 20, 20
20 X2=XM
  Y2=SLOPE*XM+B
  KK=2
  GO TO (50, 30, 40), M
25 X1=XM
  Y1=SLOPE*XM+B
  KK=1
  GO TO (50, 30, 40), M
30 IF (Y1.GT.YM*OR.Y2.GT.YM) GO TO 35
  RETURN
35 K=2
  M=7
  GO TO 10
40 IF (Y1.GT.YM*AND.Y2.GT.YM) GO TO 45
  RETURN
45 K=2
  M=7
  GO TO 10
50 RETURN
55 IF (Y2-Y1) .LE. 65, 60, 60
60 Y2=YM
  X2=(YM-B)/SLOPE
  KK=2
  GO TO (75, 70), M
65 Y1=YM
  X1=(YM-B)/SLOPE
  KK=1
  GO TO (75, 70), M
70 KK=3
75 RETURN
80 IF (SLOPE) .GE. 85, 90, 90
85 K=1
  M=3
  GO TO 10
90 K=1
  M=2

-53-
GO TO 10

95 IF (Y-Z-Y1) 125,100,100

100 Y2=Y4
    KK=2
    RETURN

105 Y1=YM
    KK=1
    RETURN
    END