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A COMPUTER PROGRAM FOR ELF/VLF PULSE PROPAGATION IN A LATERALLY--ETC(U)
AUG 79 R A PAPPERT , L R SHOCKEY
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Technical Report 444

A COMPUTER PROGRAM FOR ELF/VLF PULSE PROPAGATION IN A LATERALLY HOMOGENEOUS EARTH-IONOSPHERE WAVEGUIDE

R. A. Pappert
L. R. Shockey

31 August 1979

Interim Report: February — June 1979

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This report contains a computer program designed to handle pulse propagation problems when the propagation channel is the earth-ionosphere waveguide. The program is intended for use in the elf/vlf bands for laterally homogeneous channels. Mode data as a function of frequency from a waveguide program are required inputs to the present program. The mode data are interpolated using cubic splines, and the requisite integrals are treated numerically by means of the fast Fourier transform.

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SUMMARY

OBJECTIVE

Develop a computer program for calculating the pulse distortion and delay of vlf/elf signals in the earth-ionosphere waveguide.

RESULTS

Sample applications of the program developed to meet the objective include calculation of a slow wave elf tail generated by a median lightning discharge and a system study appropriate to the vlf communications band.

CONTENTS

I. INTRODUCTION

This report describes and lists a computer program designed to handle pulse propagation problems when the propagating channel is the earth-ionosphere waveguide and is intended for use in the elf/vlf bands. Inputs are mode data (i.e., eigenangles and excitation factors) as a function of frequency as determined, for example, by the waveguide program of Ref. 1. The mode data are interpolated using cubic splines. That is, the real and imaginary parts of the eigenangles as well as the magnitude and phase of the excitation factor are approximated by a third-degree polynomial between each pair of data points. The polynomials are determined such that they fit the input data and are twice continuously differentiable in the domain of interest. The pulse shape integrals (which are Fourier transforms) are calculated using a fast Fourier transfor. i technique. Advantages and disadvantages of the fast Fourier transform in pulse-shape studies have been discussed by Seyler, Bloch and Flynn (Ref. 2). Its major advantage is a savings in computational time, whereas a disadvantage may be that, strictly, only periodic pulse trains may be analyzed. Thus, when a non-periodic pulse is considered, it must be treated as a periodic pulse train with period much greater than the pulse width in order to obtain adequate resolution.

At the present the program is designed to calculate only the vertical electric field (E_z) at the ground for a ground-based vertical electric dipole source. Other source and receiver orientations and altitudes can be treated by extensions of the "CHANEL" subroutine. "CHANEL" could also be extended to allow for lateral inhomogeneity of the guide via WKB or mode conversion methods. The program was developed primarily as a tool for calculating slow-tail atmospheric waveforms (i.e., wave shapes in the elf band generated by lightning discharges). Because anisotropy of the ionosphere is included in calculating the input mode parameters, the program is particularly suited to studies relating to geomagnetic influences on such waveforms. It can also be used to examine atmospheric signatures in the vlf band and to conduct performance studies on proposed or existing spread spectrum systems which operate in the elf/vlf bands.

The mathematical problem at hand simply reduces to the calculation of a Fourier integral for which the integral is made up of a transmitter spectrum, receiver spectrum, and channel spectrum, each of which will be discussed more fully in the following section. Sections III and IV describe the program, Sections V and VI contain output description and some sample results. The appendix contains a program listing.

II. CHANNEL, RECEIVER AND SOURCE MODELS

In this section equations used for calculating a receiver output waveform, $G(\rho,t)$, related to the vertical electric field at the ground, will be given. In terms of the great circle range, ρ, the waveform is given by ($i = \sqrt{-1}$)

$$G(\rho,t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} idl(\omega) r(\omega) h(\omega,\rho)\, e^{j\omega t} d\omega$$

$$= \frac{1}{\pi} \mathrm{Re} \int_{0}^{\infty} idl(\omega) r(\omega) h(\omega,\rho)\, e^{j\omega t} d\omega$$

$$= 2R_e \int_{0}^{\infty} IdL(F) R(F) H(F,\rho)\, e^{j2\pi Ft} dF \qquad (1)$$

where

$$IdL(F) = idl(\omega) = idl(2\pi F), \qquad \text{source function (ampere-m/Hz)} \qquad (2)$$

$$R(F) = r(\omega) = r(2\pi F), \qquad \text{receiver function} \qquad (3)$$

$$H(F,\rho) = h(\omega,\rho) = h(2\pi F,\rho), \qquad \text{channel function} \qquad (4)$$

The second and third equalities in Eq. (1) follow from the requirement that $G(\rho,t)$ be a real quantity so that

$$IdL(F) = [IdL(-F)]^*, \; R(F) = R^*(-F) \text{ and } H(F,\rho) = H^*(-F,\rho) \qquad (5)$$

where the asterisk denotes the complex conjugate. The receiver, source and channel functions are described below:

RECEIVER

RECVR(F) is a subroutine which can be easily modified or replaced to accommodate the individual users needs. The particular RECVR(F) subroutine contained in the program listing in the appendix can be used with any receiver function of the form

$$r(\omega) = \frac{GA \left(\frac{j\omega}{\omega_1}\right)^P}{\left(1 + \frac{j\omega}{\omega_1}\right)^P \left(1 + \frac{j\omega}{\omega_2}\right)^Q} \qquad (6)$$

where the gain, GA, angular frequencies ω_1 and ω_2 and integers P and Q are read into the program via namelist. This receiver function description allows for a broad, but by no means exhaustive, class of realistic receivers. Observe that it satisfies the condition specified in Eq. (5).

TRANSMITTER

TRXMTR(F) is a subroutine which too can be readily altered to meet the specific needs of the user. Since the principal motivation for the present program was to study the shape of slow wave tails associated with atmospheric discharges, the particular source function contained in the subroutine TRXMTR(F) in the program listing in the appendix is the Williams (Ref. 3) mean source description for a lightning discharge, which is given by

$$idl(\omega) = v_o \sum_{n=1}^{4} \frac{A_n}{(\gamma_n + j\omega)^2} \left(1 - \frac{\exp[-\tau_p(\gamma_n + j\omega)]}{1 + \tau_v(\gamma_n + j\omega)}\right) \tag{7}$$

where

$$\left.\begin{array}{ll} A_1 = -16.8 \times 10^3 \text{ amperes} & \gamma_1 = 5.88 \times 10^5 \text{ sec}^{-1} \\ A_2 = 15.35 \times 10^3 \text{ amperes} & \gamma_2 = 3.03 \times 10^4 \text{ sec}^{-1} \\ A_3 = 10^3 \text{ amperes} & \gamma_3 = 2.0 \times 10^3 \text{ sec}^{-1} \\ A_4 = 0.45 \times 10^3 \text{ amperes} & \gamma_4 = 1.47 \times 10^2 \text{ sec}^{-1} \\ \tau_p = 43\ \mu\text{sec} & \tau_v = 180\ \mu\text{sec} \\ v_o = 3.5 \times 10^7 \text{ m/sec} & \end{array}\right\} \tag{8}$$

The A_i's, γ_i's, τ_p, τ_v and v_o are read into the program via namelist. The units of amperes for the A's and m/sec for v_o coupled with the channel defined in the following subsection yields a waveform in units of volts/m, which, as stated, is related to the vertical electric field at the ground. For a flat receiver the waveform would be proportional to the field, the proportionality constant being the receiver gain, GA.

CHANNEL

The channel function for the earth-ionosphere waveguide with a ground-based vertical electric dipole source is

$$H(F,\rho) = \frac{9.02 \times 10^{-14}(jF)^{3/2}}{[\sin(\rho/a)]^{1/2}} \sum_n \lambda_{vn}\, e^{-j2\pi F(SI_n - 1)\rho/c} \tag{9}$$

where

- F = freq in Hz
- c = speed of light in vacuum (km/sec)
- ρ = transmitter-receiver distance (km)
- a = earth's radius (6370 km)
- SI_n = sine of the eigenangle for the n^{th} mode

$$\lambda_{vn} = \frac{SI_n^{5/2}}{\left.\frac{\partial W}{\partial \theta}\right)_n} \frac{(1 + {}_\parallel R_\parallel)^2 (1 - {}_\perp R_\perp {}_\perp R_\perp)}{{}_\parallel R_\parallel} = \text{Excitation factor for ground-based vertical dipole} \tag{10}$$

where

- ${}_\parallel R_\parallel$ = Fresnel TM ground reflection coefficient
- ${}_\perp R_\perp$ = Fresnel TE ground reflection coefficient
- ${}_\perp R_\perp$ = TE plane wave ionospheric reflection coefficient
- ${}_\parallel R_\parallel$ = TM plane wave ionospheric reflection coefficient

$_{\parallel}R_{\perp}$ = TM to TE plane wave ionospheric conversion coefficient

$_{\perp}R_{\parallel}$ = TE to TM plane wave ionospheric conversion coefficient

$\left.\frac{\partial W}{\partial \theta}\right)_n$ = derivative of modal equation at eigenangle θ_n

$W = (1 - {}_{\parallel}R_{\parallel}\,{}_{\parallel}R_{\parallel})(1 - {}_{\perp}R_{\perp}\,{}_{\perp}R_{\perp}) - {}_{\perp}R_{\parallel}\,{}_{\parallel}R_{\perp}\,{}_{\parallel}R_{\parallel}\,{}_{\perp}R_{\perp}$ = modal function

All reflection and conversion coefficients are referenced to the ground. The channel function, $H(f,\rho)$, is defined such that the waveform associated with the vertical electric field at the ground

$$G(\rho,t) = 2R_e \int_0^{\infty} IdL(F)\,R(F)\,H(F,\rho)\,e^{j2\pi Ft}\,dF \qquad (11)$$

is in volts/m when $Idl(F) = idl(\omega) = idl(2\pi F)$ is in ampere-m/Hz. In the lower elf band, except within a few degrees of broadside, Eq. (9) can be used for a ground-based horizontal dipole radiator, such as the Wisconsin Test Facility, if the excitation factor for the single mode (termed the N=1 mode) that propagates at that frequency is replaced by

$$\lambda_{v1} \cos \psi/(N_g S I_1) \qquad (12)$$

where

λ_{v1} is given by Eq. (10)

$$N_g = \sqrt{\frac{\sigma}{j\omega\epsilon_o} + \frac{\epsilon}{\epsilon_o}} = \text{complex ground refractive index} \qquad (13)$$

where

σ = ground conductivity (siemens/m)

ϵ = ground permittivity (farads/m)

ϵ_o = permittivity of free space = 8.85×10^{-12} farads/m

and where ψ is the angle between the direction of the horizontal dipole and the direction of propagation.

III. DESCRIPTION OF INPUT

All input to the pulse shape program is read in via the card reader. A listing of a sample input showing the data deck set-up is given on pages 9 and 10. This sample input applies to a single-mode case.

There are three parts to the input. The first part is plot identification. The second part is general input read in by means of a namelist format. The third part is mode data. Each part will be discussed in further detail below.

The first part of the input consists of three cards containing plot label information. All cards are read in using a 10A4 format. The first card contains from 1 to 40 alphanumeric characters containing whatever information the user wishes to be printed on the transmitter spectrum plot. The second and third cards are identical in format and contain information for the receiver spectrum plot and the channel spectrum plot, respectively.

The second part of the input is read in by means of an ASCII FORTRAN namelist input format. The following variables and arrays may be specified in the namelist input.

NM	–	maximum number of modes to be read in (note that the program allows the number of modes read in to vary with frequency)
NEVF	–	indicates which quantities are to be fitted by a cubic spline (XTRMAG, XTRANG, RETHP, IMTHP, ATT and PHVOC are mode inputs to be described subsequently).
NEVF(1) ≠ 1	–	then a cubic spline fit is applied to XTRMAG.
NEVF(2) ≠ 1	–	then a cubic spline fit is applied to XTRANG.
NEVF(3) ≠ 1	–	then a cubic spline fit is applied to RETHP.
NEVF(4) ≠ 1	–	then a cubic spline fit is applied to IMTHP.
NEVF(5) ≠ 1	–	then a cubic spline fit is applied to PHVOC.
NEVF(6) ≠ 1	–	then a cubic spline fit is applied to ATT.
N - 2^N	–	is the number of integration intervals in the frequency range (FU-FL).
FU	–	upper frequency of integration in kilohertz.
FL	–	lower frequency of integration in kilohertz.
NF	–	number of frequencies.
A	–	an array of four elements used to describe the source function given in Eq. (7). The units of A are amperes.
GAM	–	an array of four elements used to describe the source function given in Eq. (7). The units of GAM (γ in the equation) are inverse seconds.
TAUP	–	characteristic time in seconds associated with the source function given in Eq. (7).
TAUV	–	characteristic time in seconds associated with the source function given in Eq. (7).
V0	–	characteristic velocity in m/sec associated with the source function given in Eq. (7).
GA	–	gain for the receiver function given in Eq. (6).
OMEGA1	–	angular frequency for the receiver function given in Eq. (6).
OMEGA2	–	angular frequency for the receiver function given in Eq. (6).
P	–	integer variable used in the receiver function given in Eq. (6).
Q	–	integer variable used in the receiver function given in Eq. (6).
RHO	–	transmitter-receiver distance in kilometres used in mode sum.

S — S = 1 for positive Fourier transform
S = −1 for negative Fourier transform.

INTPRT — flag to control the print interval. The first 20 values are printed and then every INTPRTth one. For example if INTPRT = 10 then the 1st 20 values are printed followed by the 30th, 40th, 50th . . . every 10th value out to the end.

IPLOT — flag to determine whether or not plots are drawn.
If IPLOT = 0 no plots are generated.
If IPLOT = 1 six plots are generated: source spectrum, receiver spectrum, channel spectrum, product spectrum (source*receiver*channel), output waveform, and the input current pulse.

TMIN — an array of three elements used to describe the starting time in seconds for the input current pulse plot.

TINC — an array of three elements used to describe the time increment in seconds for the input current pulse plot.

NUMTS — an array of three elements used to describe the number of times that are plotted on the input current pulse plot.

TAUMAX — controls the latest time in seconds plotted on the output waveform curve.

The mode data or third part of the input follows the namelist input. The eight columns of mode data on pages 9 and 10 are:

NMF — number of modes at FREQ(I), I = 1, 2, . . ., NF (column 1).

RETHP(M,I) — the real part of the complex ground eigenangle for mode M and frequency I in degrees (column 2).

IMTHP(M,I) — the imaginary part of the complex ground eigenangle for mode M and frequency I in degrees (column 3).

XTRMAG(M,I) — magnitude of excitation factor for mode M and frequency I (column 4).

XTRANG(M,I) — phase (in radians) of excitation factor for mode M and frequency I (column 5).

FREQ(I) — frequencies in kilohertz for which mode data is input (column 6).

ATT(M,I) — attenuation rate in dB/1000 km for mode M and frequency I (column 7).

PHVOC(M,I) — phase velocity over free-space velocity for mode M and frequency I (column 8).

The mode data input shown on pages 9 and 10 is for a single mode case. A sample input of mode data for a multimode case is shown on pages 11 and 12. The eight columns have the same meaning as above. The ordering is such that all modes for the first frequency are followed by all modes for the second frequency, etc. It should be mentioned that the attenuation and phase velocity inputs are not used directly in the calculations. They are included in the input so that they may, at the users option, be spline fit for the purpose of explicitly exhibiting their frequency dependence.

Sample input - single mode case

```
RECORD        COLUMN 1
              ↓
  1           WILLIAMS SOURCE
  2           P=2 Q=2 F1=10HZ F2=2500HZ
  3           SATELLITE NIGHT A=254 C=47 RHO=3700 KM
  4            &DATUM
  5            A=-16800.,15350.,1000.,450.,
  6            GAM=5.882353D5,3.030303D4,2000.,147.0588,
  7            TAUP=.43D-4,TAUV=.18D-3,
  8            V0=3.5D7,
  9            GA=1.0,
 10            OMEGA1=62.8318530717958648,
 11            OMEGA2=.1570796326D5,
 12            P=2,Q=2,RHO=.3700D4,
 13            NM=1,          N=11,FU=3.0,FL=0.0, NF=50,
 14            NEVF=0,0,0,0,1,1,
 15            S=1.0,
 16            INTPRT=20,
 17            IPLOT=1,
 18            TAUMAX=.03,
 19            TMIN=0.,100.0E-6,1000.0E-6,
 20            TINC=1.0E-6,10.0E-6,100.0E-6,
 21            NUMTS=101,91,91,
 22            &END
 23              1  68.68144 -89.85283   .449550+004    .69310   .00100    .15188    .42882
 24              1  71.83926 -85.25623   .172290+004    .81145   .00200    .23844    .45226
 25              1  70.83997 -85.45403   .105810+004    .81214   .00300    .37807    .45352
 26              1  65.42609 -88.16844   .794070+003    .69138   .00400    .67295    .45123
 27              1  52.19470 -87.80942   .579400+003    .37654   .00500   1.23140    .52235
 28              1  39.11598 -75.83609   .327980+003    .10674   .00600   1.47910    .78799
 29              1  36.01082 -59.41103   .175050+003    .12655   .00700   1.27095   1.07139
 30              1  39.91328 -46.13422   .109400+003    .35572   .00800    .99982   1.16130
 31              1  47.13419 -37.47762   .848150+002    .63971   .00900    .78216   1.11680
 32              1  54.52582 -33.55458   .763410+002    .84465   .01000    .65468   1.04377
 33              1  77.38156 -32.89455   .426530+002   1.27027   .02000    .48214    .87632
 34              1  81.30551 -34.23759   .287370+002   1.34840   .03000    .52321    .85447
 35              1  83.61436 -33.82635   .168860+002   1.40841   .05000    .63300    .85318
 36              1  84.46935 -33.75917   .119480+002   1.43398   .07000    .76624    .85239
 37              1  84.34766 -33.82622   .924160+001   1.44020   .09000   1.00900    .85204
 38              1  84.04839 -33.49306   .748780+001   1.44166   .11000   1.28407    .85511
 39              1  83.80910 -33.08896   .627250+001   1.44255   .13000   1.55719    .85865
 40              1  83.42812 -32.79770   .538950+001   1.44027   .15000   1.88827    .86156
 41              1  82.82845 -31.60588   .414970+001   1.43893   .19000   2.50458    .87184
 42              1  82.91234 -30.90227   .337460+001   1.44516   .23000   2.92346    .87702
 43              1  82.62984 -30.64050   .284340+001   1.44477   .27000   3.53487    .87954
 44              1  82.17039 -30.36458   .244700+001   1.44236   .31000   4.26764    .88255
 45              1  81.54906 -30.07123   .213900+001   1.43957   .35000   5.14323    .88611
 46              1  80.83212 -29.57426   .188780+001   1.43508   .39000   6.10152    .89152
 47              1  80.28786 ¬28.93816   .168260+001   1.43605   .43000   6.95682    .89760
 48              1  79.88225 -28.36197   .151390+001   1.43865   .47000   7.74785    .90290
 49              1  79.59653 -27.99237   .140710+001   1.44167   .50000   8.35351    .90637
 50              1  79.08374 -27.37440   .125630+001   1.44758   .55000   9.40758    .91231
 51              1  78.49643 -26.78851   .113030+001   1.45382   .60000  10.55963    .91829
```

52	1	77.81978	-26.18755	.102610+001	1.46133	.65000	11.81226	.92475
53	1	77.11584	-25.40312	.936710+000	1.47078	.70000	13.01488	.93265
54	1	76.51765	-24.37708	.860280+000	1.48212	.75000	13.95552	.94180
55	1	76.19249	-23.25522	.794720+000	1.49519	.80000	14.49780	.95039
56	1	76.07784	-22.15001	.738670+000	1.51104	.85000	14.75402	.95780
57	1	76.19983	-21.17859	.690780+000	1.52625	.90000	14.77714	.96317
58	1	76.40427	-20.39687	.649520+000	1.54151	.95000	14.77984	.96691
59	1	76.62453	-19.74634	.612700+000	1.55567	1.00000	14.80253	.96972
60	1	76.82541	-19.20427	.580090+000	1.56965	1.05000	14.87718	.97192
61	1	76.99203	-18.71765	.550760+000	1.58318	1.10000	14.98796	.97390
62	1	77.15527	-18.25623	.524280+000	1.59640	1.15000	15.08144	.97572
63	1	77.32137	-17.82993	.500120+000	1.60922	1.20000	15.16243	.97729
64	1	77.50592	-17.41942	.478300+000	1.62168	1.25000	15.19845	.97868
65	1	77.70125	-17.07767	.457960+000	1.63377	1.30000	15.24871	.97965
66	1	77.87224	-16.79086	.439170+000	1.64636	1.35000	15.34853	.98043
67	1	78.09857	-16.49651	.421840+000	1.65831	1.40000	15.34278	.98102
68	1	78.24117	-16.28906	.405570+000	1.67129	1.45000	15.50024	.98150
69	1	78.36169	-16.10445	.390360+000	1.68406	1.50000	15.68804	.98195
70	1	78.45825	-15.93717	.376170+000	1.69704	1.55000	15.90699	.98239
71	1	78.71213	-14.75822	.285060+000	1.84370	2.00000	18.56023	.98681
72	1	77.55756	-13.36197	.243710+000	2.04625	2.50000	23.07573	.99682

Sample mode data input - multimode case

5	89.68719	-3.51977	.459513-001	1.67011	20.00000	1.22187	.99813
5	87.60259	-1.22813	.250220-003	3.61597	20.00000	3.26476	1.00065
5	81.92853	-.56878	.802365-001	1.58915	20.00000	5.07488	1.00996
5	78.62587	-.77169	.396147-003	3.81155	20.00000	9.67112	1.01994
5	74.55770	-.77943	.705413-001	1.53383	20.00000	13.18052	1.03731
5	89.69419	-3.57576	.445279-001	1.67252	20.30000	1.23176	.99807
5	87.80930	-1.32117	.252105-003	3.59143	20.30000	3.25761	1.00047
5	82.10618	-.56475	.793966-001	1.58888	20.30000	5.00265	1.00952
5	78.83583	-.76580	.387788-003	3.79457	20.30000	9.56374	1.01920
5	74.83754	-.76826	.697360-001	1.58864	20.30000	12.96089	1.03597
5	89.71299	-3.74530	.400282-001	1.68120	21.30000	1.27057	.99788
5	88.42537	-1.74278	.259823-003	3.50916	21.30000	3.24147	.99992
5	82.66762	-.55381	.767643-001	1.58816	21.30000	4.78338	1.00820
5	79.49777	-.74846	.362270-003	3.73917	21.30000	9.23286	1.01695
5	75.68359	-.73517	.672087-001	1.58801	21.30000	12.30307	1.03197
5	89.72650	-3.89364	.358760-001	1.69091	22.30000	1.31789	.99771
5	88.83762	-2.25107	.269979-003	3.42492	22.30000	3.23633	.99943
5	83.18720	-.54629	.743525-001	1.58780	22.30000	4.59161	1.00707
5	80.10773	-.73434	.340106-003	3.68456	22.30000	8.93879	1.01501
5	76.45414	-.70750	.649029-001	1.58737	22.30000	11.74152	1.02953
5	89.73176	-3.96148	.339200-001	1.69516	22.80000	1.34459	.99763
5	88.97237	-2.49115	.276052-003	3.38147	22.80000	3.23753	.99922
5	83.43321	-.54368	.732152-001	1.58777	22.80000	4.50418	1.00656
5	80.39549	-.72836	.330055-003	3.65785	22.80000	8.80361	1.01413
5	76.81451	-.69536	.638255-001	1.58704	22.80000	11.49053	1.02700
5	89.73271	-3.97461	.335331-001	1.69724	22.90000	1.35017	.99751
5	88.99515	-2.53688	.277288-003	3.37305	22.90000	3.23806	.99917
5	83.48140	-.54325	.729926-001	1.58778	22.90000	4.48732	1.00646
5	80.45177	-.72725	.328127-003	3.65253	22.90000	8.77749	1.01397
5	76.88475	-.69305	.636157-001	1.58697	22.90000	11.44239	1.02671
5	89.73363	-3.98759	.331590-001	1.69833	23.00000	1.35582	.99759
5	89.01675	-2.58178	.278595-003	3.35428	23.00000	3.23866	.99913
5	83.52926	-.54284	.727715-001	1.58779	23.00000	4.47059	1.00637
5	80.50763	-.72617	.326205-003	3.64723	23.00000	8.75170	1.01380
5	76.95439	-.69079	.634078-001	1.58691	23.00000	11.39511	1.02642
5	89.73452	-4.00045	.327831-001	1.69943	23.10000	1.36155	.99758
5	89.03724	-2.62587	.279932-003	3.35552	23.10000	3.23939	.99909
5	83.57681	-.54246	.725519-001	1.58780	23.10000	4.45406	1.00627
5	80.56309	-.72511	.324296-003	3.64213	23.10000	8.72611	1.01364
5	77.02345	-.68856	.632017-001	1.58684	23.10000	11.34836	1.02613
5	89.73538	-4.01317	.324100-001	1.70054	23.20000	1.36735	.99756
5	89.05671	-2.66914	.281287-003	3.34676	23.20000	3.24019	.99905
5	83.62403	-.54211	.723337-001	1.58782	23.20000	4.43772	1.00618
5	80.61815	-.72408	.322421-003	3.63676	23.20000	8.70083	1.01348
5	77.09193	-.68636	.629975-001	1.58677	23.20000	11.30213	1.02585
5	89.73621	-4.02576	.320399-001	1.70166	23.30000	1.37324	.99755
5	89.07523	-2.71159	.282674-003	3.33792	23.30000	3.24105	.99901
5	83.67095	-.54179	.721169-001	1.58785	23.30000	4.42158	1.00609
5	80.67282	-.72307	.320602-003	3.63148	23.30000	8.67575	1.01332
5	77.15985	-.68421	.627950-001	1.58671	23.30000	11.25675	1.02557
6	89.73701	-4.03823	.316727-001	1.70280	23.40000	1.37922	.99753
6	89.09284	-2.75323	.284104-003	3.32894	23.40000	3.24205	.99897
6	83.71755	-.54150	.719015-001	1.58788	23.40000	4.40563	1.00600
6	80.72709	-.72209	.318762-003	3.62631	23.40000	8.65099	1.01316

6	77.22720	-.68209	.625943-001	1.58664	23.40000	11.21191	1.02530
6	74.57598	-.92397	.635329-003	3.67583	23.40000	18.27093	1.03723
6	89.73778	-4.05057	.313034-001	1.70394	23.50000	1.38528	.99752
6	89.10963	-2.79408	.289538-003	3.32002	23.50000	3.24310	.99893
6	83.76386	-.54123	.716374-001	1.58791	23.50000	4.38978	1.00591
6	80.78098	-.72114	.316979-003	3.62107	23.50000	8.62654	1.01301
6	77.29399	-.68001	.623554-001	1.58657	23.50000	11.16775	1.02503
6	74.65101	-.92117	.630618-003	3.67089	23.50000	18.20656	1.03685
6	89.73853	-4.06279	.309470-001	1.70509	23.60000	1.39139	.99750
6	89.12563	-2.83414	.287027-003	3.31097	23.60000	3.24427	.99889
6	83.80986	-.54099	.714747-001	1.58795	23.60000	4.37413	1.00582
6	80.83449	-.72021	.315217-003	3.61587	23.60000	8.60229	1.01285
6	77.36025	-.67796	.621982-001	1.58650	23.60000	11.12410	1.02476
6	74.72542	-.91841	.626093-003	3.66587	23.60000	18.14298	1.03649
6	89.73926	-4.07490	.305865-001	1.70625	23.70000	1.39755	.99749
6	89.14090	-2.87343	.288512-003	3.30198	23.70000	3.24554	.99886
6	83.85558	-.54078	.712631-001	1.58800	23.70000	4.35865	1.00573
6	80.88764	-.71931	.313440-003	3.61066	23.70000	8.57834	1.01270
6	77.42597	-.67594	.620328-001	1.58644	23.70000	11.08098	1.02450
6	74.79923	-.91568	.621509-003	3.66098	23.70000	18.07999	1.03612
6	89.73996	-4.08690	.302327-001	1.70743	23.80000	1.40380	.99747
6	89.15550	-2.91196	.290007-003	3.29309	23.80000	3.24685	.99882
6	83.90100	-.54060	.710528-001	1.58805	23.80000	4.34336	1.00565
6	80.94041	-.71843	.311715-003	3.60548	23.80000	8.55458	1.01255
6	77.49115	-.67396	.618391-001	1.58637	23.80000	11.03854	1.02424
6	74.87245	-.91298	.616933-003	3.65607	23.80000	18.01758	1.03577
6	89.74310	-4.14524	.284931-001	1.71344	24.30000	1.43624	.99740
6	89.21964	-3.09360	.293033-003	3.24718	24.30000	3.25477	.99864
6	84.12394	-.54008	.700185-001	1.58837	24.30000	4.26898	1.00524
6	81.19892	-.71441	.303314-003	3.57992	24.30000	8.43957	1.01184
6	77.80939	-.66453	.608656-001	1.58602	24.30000	10.83436	1.02300
6	75.22985	-.89999	.595212-003	3.63170	24.30000	17.71555	1.03405
6	89.74787	-4.25471	.252259-001	1.72623	25.30000	1.50640	.99726
6	89.31552	-3.41016	.315986-003	3.15280	25.30000	3.27666	.99830
6	84.55051	-.54103	.630222-001	1.58944	25.30000	4.13027	1.00450
6	81.69104	-.70817	.288060-003	3.52943	25.30000	8.22662	1.01053
6	78.40996	-.64765	.590972-001	1.58530	25.30000	10.46290	1.02075
6	75.90414	-.87624	.555064-003	3.58397	25.30000	17.15501	1.03092
6	89.75103	-4.35617	.222143-001	1.74000	26.30000	1.58326	.99713
6	89.38370	-3.67575	.336685-003	3.05295	26.30000	3.30607	.99800
6	84.95442	-.54471	.660966-001	1.59110	26.30000	4.00319	1.00384
6	82.15344	-.70422	.274332-003	3.48056	26.30000	8.03387	1.00938
6	78.96759	-.63370	.574746-001	1.58455	26.30000	10.13352	1.01877
6	76.52979	-.85514	.518840-003	3.53768	26.30000	16.64578	1.02817
6	89.75249	-4.42324	.202537-001	1.75021	27.00000	1.64080	.99704
6	89.42076	-3.83780	.352722-003	2.97946	27.00000	3.33082	.99781
6	85.22549	-.54899	.647763-001	1.59265	27.00000	3.92003	1.00344
6	82.46143	-.70277	.265614-003	3.44711	27.00000	7.90955	1.00864
6	79.33512	-.62509	.564183-001	1.58400	27.00000	9.92405	1.01752
6	76.94183	-.84176	.495532-003	3.50610	27.00000	16.31595	1.02643

IV. PROGRAM LAYOUT

This section describes the basic features of the pulse shape program listed in the appendix.

Reading and printing of input quantities occurs in MAIN. MAIN calls in order the following subroutines.

SUBROUTINE FUNSPL (MD,LF,XX,YY,B,C,D)

Inputs to FUNSPL are a mode index MD, which takes on values 1 through NM, and the index, LF, for the quantity which is to be approximated as a function of frequency by a cubic spline. LF can take on integer values 1 through 6. FUNSPL calls the two following subroutines.

a. SUBROUTINE FUNCVF (MD,XX,YY) places

XX(i) = FREQ(I), I = 1, 2, . . ., NF.

YY(K) = XTRMAG(MD,K) if LF = 1 and data read in for I=K.

YY(K) = XTRANG(MD,K) if LF = 2 and data read in for I=K.

YY(K) = RETHP(MD,K) if LF = 3 and data read in for I=K.

YY(K) = IMTHP(MD,K) if LF = 4 and data read in for I=K.

YY(K) = PHVOC(MD,K) if LF = 5 and data read in for I=K.

YY(K) = ATT(MD,K) if LF = 6 and data read in for I=K.

b. SUBROUTINE SPLINE (XX,YY,B,C,D,N) determines the coefficients B, C, D, of a cubic spline interpolating the given curve (XX(I), YY(I), I = 1, 2, . . . N). If XX(I).LE. X.LE.XX(I+1) and H=X–XX(I), then the interpolated value at X is F(X) = YY(I) + B(I) * H + C(I) * H ** 2 + D(I) * H ** 3. The interpolated value is evaluated using the function SPEVAL(XVAL,X,Y,B,C,D,N,INIT). In particular SPEVAL evaluates the interpolating cubic spline for the data (X(I), Y(I)), I = 1 . . ., N at XVAL. INIT is an estimate of the interval where XVAL lies, X(INIT).LE.XVAL.LE.X(INIT+1), but need not be used. Set INIT=0 if there is no estimate. On return, INIT will contain the interval number.

The replacements

YC(LF,MD,I) = YY(I)

BC(LF,MD,I) = B(I)

CC(LF,MD,I) = C(I)

DC(LF,MD,I) = D(I)

are then made in FUNSPL and control returned to MAIN. MAIN then calls the TRXMTR, RECVR and CHANEL subroutines at the frequency points F = (K – 1) FU–FL/2^N + FL, K = 1, 2 . . ., 2^N + 1.

SUBROUTINE TRXMTR(F) calculates the spectrum for the Williams description of the mean lightning stroke as discussed in Section II. The subroutine can be easily altered to satisfy the users needs. For example, alternative descriptions of the lightning discharge are readily accommodated. In the example in Section VI of this report illustrating results for a spread-spectrum system, the transmitter function given by Eq. (20) of that section was used.

SUBROUTINE RECVR(F) calculates the spectrum for the receiver function discussed in Section II. This subroutine is also easily altered to satisfy the user's needs. For example, the spread-spectrum system calculation presented as an example in Section VI of this report utilized the receiver function given by Eq. (21) of that section.

SUBROUTINE CHANEL(F) calculates the spectrum for the elf/vlf channel described by Eq. (9) of Section II. Specifically it is for the vertical electric field at the ground produced by a ground-based vertical electric dipole. Ground-based horizontal dipole sources can be accommodated using the replacement indicated by Eq. (12) of Section II.

The real part of the product spectrum, $Idl(F)R(F)H(F,\rho)$, which occurs in Eq. (1) of Section II is stored in X(K) and the imaginary part is stored in Y(K).

SUBROUTINE NLOGN(N,X,Y,SIGNT,A,B) calculates (apart from end point effects) integrals of the form (S=SIGNT)

$$\exp\left[-j2\pi SA\tau\right] \int_A^B (X(F) + jY(F)) \exp(j2\pi SF\tau)\, dF$$

$$= \int_0^{B-A} (X(F+A) + jY(F+A)) \exp(j2\pi SF\tau) dF \tag{14}$$

by the fast Fourier transform technique of Cooley and Tukey (Ref. 4). This makes use of digital evaluations at the frequencies

$$F(L) = \frac{L-1}{2^N}(B-A);\ L = 1, 2 \ldots, 2^N \tag{15}$$

and the method yields evaluations for the times

$$\tau(K) = \frac{K-1}{B-A};\ K = 1, 2 \ldots, 2^N. \tag{16}$$

Real and imaginary parts of the integral are then stored in X(K) and Y(K) respectively. NLOGN also has built into it the Filon weight factors

$$\frac{4(B-A)\,2^N}{(K-1)^2\,(2\pi)^2} \sin^2\left[\frac{2\pi(K-1)}{2^{N+1}}\right];\ K = 1, 2, 3 \ldots, 2^N \tag{17}$$

which for K = 1 is simply the integral size $(B-A)/2^N$. If the integrand of Eq. (14) at the points (A,B) is not negligible, it is necessary to add to X(K) and Y(K) the following end point corrections

$$\frac{B-A}{2\pi(K-1)}\left[\frac{1}{j(\text{SIGNT})} + \frac{2^N}{2\pi(K-1)}\left(1 - \exp(-jS2\pi(K-1)/2^N)\right)\right]\left[-U(1,K) + U(2^N+1,K)\right] \tag{18}$$

where the U's are the complete integrand of Eq. (14) evaluated at the frequencies [see Eq. (15)] L = 1 and L = $2^N + 1$. If K = 1 in the factors multiplying the U's in Eq. (18) the multiplying factors become one-half the interval size, $(B - A)/2^{N+1}$. If the Filon weight factors were omitted, the weight factors given by Eq. (17) would simply be replaced by $(B - A)/2^N$ and Eq. (18) by

$$\frac{B - A}{2^{N+1}} \left[-U(1,K) + U(2^N + 1,K) \right] \tag{19}$$

The quantity S=SIGNT takes on the values +1 or −1 and simply allows for plus or minus transforms as desired. It should be observed that although the region of significance of the integrand of Eq. (14) may be quite small, the integration limits A,B may of necessity be quite large in order to achieve a desired time resolution [see Eq. (16)]. N must be chosen to give small enough step sizes in the region where the integrand is significant. Specifically, step sizes must be small compared with distances (in frequency units) over which the integrand (exclusive of the exponential factor when Filon weight factors are used) changes appreciably. Also, it should be mentioned that the program can be easily altered to accommodate other integration routines should the need arise in a particular application.

V. DESCRIPTION OF OUTPUT

The sample output shown on pages 17 through 24 begins with a listing of the three plot identification lines followed by the namelist output. The mode data come next. For each frequency (given in increasing order) the number of modes, the real and imaginary parts of the eigenangle, the magnitude and phase of the excitation factor, the attenuation rate and the phase velocity normalized to free-space velocity are listed. Though the sample output is for a single-mode case, the program, as mentioned, is equally suited for multimode studies.

The principal output of the pulse shape program begins on page 19. The transmitter, receiver, channel, and product (XMTR*RCVR*CHNL) spectra are given as a function of frequency. Not all 2049 (i.e., $2^N + 1$ with N = 11) lines are listed. The printout is controlled by the namelist variable INTPRT. The first 20 values of the spectra are always printed. These are followed by every 20th value of the spectra because in this instance INTPRT = 20.

Following the spectra output comes output (page 22) pertaining to the time signature of the output waveform, $G(\rho,t)$ given by Eq. (1).

The first column is the time in seconds, the second and third columns are the real and imaginary parts, respectively, of the integral

$$\frac{1}{2\pi} \int_0^{\infty} i\, d l(\omega) r(\omega) h(\omega,\rho) \exp(j\omega t) d\omega$$

The last column is the waveform, $G(\rho,t)$, given by Eq. (1) in volts/m. $G(\rho,t)$ at time equal to zero should be zero. The departure from zero at time equal to zero is believed to be associated with truncation effects and/or discontinuities in the third and higher derivatives of the interpolated mode data. The program also generates six plots. These are:

1) transmitter spectrum vs freq
2) receiver spectrum vs freq
3) channel spectrum vs freq
4) product (transmitter*receiver*channel) spectrum vs freq
5) output waveform G vs freq
6) input current pulse vs freq

The four spectra plots are only plotted between the first and last frequency inputs (FREQ(1) - FREQ(NF)).

The output waveform is plotted out to TAUMAX (a namelist input variable).

The plots are shown in Figs. 1 through 6.

Sample output

```
WILLIAMS SOURCE
P=2 Q=2 F1=10HZ F2=2500HZ
SATELLITE NIGHT A=254 C=47 RHO=3700 KM


 $DATUM
A =-.16800000000000000+005, .15350000000000000+005, .10000000000000000+004, .45000000000000000+003,
GAM = .58823529999999999+006, .30303029999999999+005, .20000000000000000+004, .14705880000000000+003,
TAUP = .42999999999999999-004,TAUV = .18000000000000000-003,V0 = .35000000000000000+008,GA = .10000000000000000+001,
OMEGA1 = .62831853071795864 7+002,OMEGA2 = .15707963260000000+005,P =          2,Q =          2,NM =          1,
NEVF =          0,          0,          0,          0,          1,          1,N =         11,FU = .30000000000000000+001,
FL = .00000000000000000     ,NF =         50,RHO = .36999999999999999+004,S = .10000000000000000+001,INTPRT =         20,
IPLOT =          1,TAUMAX = .30000000000000000-001,
TMIN = .00000000000000000     , .10000000000000000-003, .99999999999999997-003,
TINC = .10000000000000000-005, .10000000000000000-004, .10000000000000000-003,
NUMTS =        101,         91,         91
$END
```

NMF	FREQ KHZ	THETAR DEGREES	THETAI DEGREES	XTRMAG	XTRANG RADIANS	ATT DB	PHVOC
1	.00100	68.68144	-89.85283	.449550+004	.69310	.15188	.42882
1	.00200	71.83926	-85.25623	.172290+004	.81145	.23844	.45226
1	.00300	70.83997	-85.45403	.105810+004	.81214	.37807	.45352
1	.00400	65.42609	-88.16844	.794070+003	.69138	.67295	.45123
1	.00500	52.19470	-87.80942	.579400+003	.37654	1.23140	.52235
1	.00600	39.11598	-75.83609	.327980+003	.10674	1.47910	.78799
1	.00700	36.01082	-59.41103	.175050+003	.12655	1.27095	1.07139
1	.00800	39.91328	-46.13422	.109400+003	.35572	.99982	1.16130
1	.00900	47.13419	-37.47762	.848150+002	.63971	.78216	1.11680
1	.01000	54.52582	-33.55458	.763410+002	.84465	.65468	1.04377
1	.02000	77.38156	-32.89455	.426530+002	1.27027	.48214	.87632
1	.03000	81.30551	-34.23759	.287370+002	1.34840	.52321	.85447
1	.05000	83.61436	-33.82635	.168860+002	1.40841	.63300	.85318
1	.07000	84.46935	-33.75917	.119480+002	1.43398	.76624	.85239
1	.09000	84.34766	-33.82622	.924160+001	1.44020	1.00900	.85204
1	.11000	84.04839	-33.49306	.748780+001	1.44166	1.28407	.85511
1	.13000	83.80910	-33.08896	.627250+001	1.44255	1.55719	.85865
1	.15000	83.42812	-32.79770	.538950+001	1.44027	1.88827	.86156
1	.19000	82.82845	-31.60588	.414970+001	1.43893	2.50458	.87184
1	.23000	82.91234	-30.90227	.337460+001	1.44516	2.92346	.87702
1	.27000	82.62984	-30.64050	.284340+001	1.44477	3.53487	.87954
1	.31000	82.17039	-30.36458	.244700+001	1.44236	4.26764	.88255
1	.35000	81.54906	-30.07123	.213900+001	1.43957	5.14323	.88611
1	.39000	80.83212	-29.57426	.188780+001	1.43508	6.10152	.89152
1	.43000	80.28786	-28.93816	.168260+001	1.43605	6.95682	.89760
1	.47000	79.88225	-28.36197	.151390+001	1.43865	7.74785	.90290
1	.50000	79.59653	-27.99237	.140710+001	1.44167	8.35351	.90637
1	.55000	79.08374	-27.37440	.125630+001	1.44758	9.40758	.91231
1	.60000	78.49643	-26.78851	.113030+001	1.45382	10.55963	.91829
1	.65000	77.81978	-26.18755	.102610+001	1.46133	11.81226	.92475
1	.70000	77.11584	-25.40312	.936710+000	1.47078	13.01488	.93265
1	.75000	76.51765	-24.37708	.860280+000	1.48212	13.95552	.94180
1	.80000	76.19249	-23.25522	.794720+000	1.49519	14.49780	.95039
1	.85000	76.07784	-22.15001	.738670+000	1.51104	14.75402	.95780
1	.90000	76.19983	-21.17359	.690780+000	1.52625	14.77714	.96317
1	.95000	76.40427	-20.39687	.649520+000	1.54151	14.77984	.96691
1	1.00000	76.62453	-19.74634	.612700+000	1.55567	14.80253	.96972
1	1.05000	76.82541	-19.20427	.580090+000	1.56965	14.87718	.97192
1	1.10000	76.99203	-18.71765	.550760+000	1.58318	14.98796	.97390
1	1.15000	77.15527	-18.25623	.524280+000	1.59640	15.08144	.97572
1	1.20000	77.32137	-17.82993	.500120+000	1.60922	15.16243	.97729
1	1.25000	77.50592	-17.41942	.478300+000	1.62168	15.19845	.97868
1	1.30000	77.70125	-17.07767	.457960+000	1.63377	15.24871	.97965
1	1.35000	77.87224	-16.79086	.439170+000	1.64636	15.34853	.98043
1	1.40000	78.09857	-16.49651	.421840+000	1.65831	15.34278	.98102
1	1.45000	78.24117	-16.28906	.405570+000	1.67129	15.50024	.98150
1	1.50000	78.36169	-16.10445	.390360+000	1.68406	15.68804	.98195
1	1.55000	78.45825	-15.93717	.376170+000	1.69704	15.90699	.98239
1	2.00000	78.71213	-14.75822	.285060+000	1.84370	18.56023	.98681
1	2.50000	77.55756	-13.36197	.243710+000	2.04625	23.07573	.99682

FREQ(HZ)	XMTR R	XMTR I	RCVR R	RCVR I	CHNL R	CHNL I	XMTR*RCVR*CHNL REAL	XMTR*RCVR*CHNL IMAG	K
.00000	.26658+005	.00000	.00000	.00000	.00000	.00000	.00000	.00000	1
.14648+001	.26565+005	-.15049+004	-.20117-001	.60487-002	-.58953-009	.10209-009	.29019-006	-.16620-006	2
.29297+001	.26290+005	-.29754+004	-.66449-001	.42811-001	-.54416-009	.13499-009	.70267-006	-.93865-006	3
.43945+001	.25844+005	-.43795+004	-.10904+000	.11962+000	-.45071-009	.30658-009	-.60124-007	-.23120-005	4
.58594+001	.25249+005	-.56903+004	-.12389+000	.22354+000	-.22739-009	.24106-009	-.11085-005	-.18911-005	5
.73242+001	.24526+005	-.68871+004	-.10339+000	.33348+000	-.18428-009	.10999-009	-.93392-006	-.16647-005	6
.87891+001	.23704+005	-.79560+004	-.52903-001	.43259+000	-.19542-009	.24037-010	-.68411-006	-.20335-005	7
.10254+002	.22809+005	-.88902+004	.17051-001	.51224+000	-.22728-009	-.28192-010	-.79828-006	-.27603-005	8
.11719+002	.21866+005	-.96888+004	.96365-001	.57055+000	-.25519-009	-.70277-010	-.11373-005	-.34820-005	9
.13184+002	.20899+005	-.10356+005	.17754+000	.60943+000	-.27716-009	-.10282-009	-.16571-005	-.40509-005	10
.14648+002	.19928+005	-.10900+005	.25586+000	.63228+000	-.29727-009	-.12238-009	-.23637-005	-.43840-005	11
.16113+002	.18969+005	-.11331+005	.32876+000	.64271+000	-.31740-009	-.12838-009	-.32038-005	-.44228-005	12
.17578+002	.18034+005	-.11659+005	.39513+000	.64389+000	-.33708-009	-.12263-009	-.40735-005	-.41556-005	13
.19043+002	.17132+005	-.11899+005	.45474+000	.63840+000	-.35483-009	-.10929-009	-.48557-005	-.36425-005	14
.20508+002	.16270+005	-.12061+005	.50785+000	.62826+000	-.37004-009	-.94671-010	-.54737-005	-.30156-005	15
.21973+002	.15452+005	-.12156+005	.55498+000	.61495+000	-.38364-009	-.83540-010	-.59277-005	-.23982-005	16
.23438+002	.14680+005	-.12196+005	.59671+000	.59960+000	-.39657-009	-.76299-010	-.62573-005	-.18310-005	17
.24902+002	.13954+005	-.12188+005	.63365+000	.58300+000	-.40936-009	-.72645-010	-.64986-005	-.13273-005	18
.26367+002	.13275+005	-.12143+005	.66638+000	.56575+000	-.42225-009	-.71965-010	-.66779-005	-.88545-006	19
.27832+002	.12640+005	-.12066+005	.69543+000	.54825+000	-.43517-009	-.73339-010	-.68111-005	-.49404-006	20
.57129+002	.60905+004	-.89799+004	.92620+000	.28740+000	-.57153-009	.79374-010	-.41778-005	.44057-005	40
.86426+002	.41496+004	-.68966+004	.97282+000	.15827+000	-.54715-009	.30601-009	-.95387-006	.48809-005	60
.11572+003	.32770+004	-.57392+004	.98731+000	.79041-001	-.39777-009	.45289-009	.98159-006	.38216-005	80
.14502+003	.27401+004	-.50370+004	.99169+000	.21631-001	-.21806-009	.50650-009	.18837-005	.25078-005	100
.17432+003	.23399+004	-.45653+004	.99160+000	-.24418-001	-.78617-010	.47663-009	.20113-005	.14132-005	120
.20361+003	.20104+004	-.42169+004	.98897+000	-.63763-001	.18867-010	.43867-009	.19181-005	.67314-006	140
.23291+003	.17268+004	-.39376+004	.98463+000	-.98767-001	.11964-009	.39082-009	.17388-005	.26241-007	160
.26221+003	.14785+004	-.36992+004	.97899+000	-.13074+000	.19151-009	.30058-009	.13312-005	-.44087-006	180
.29150+003	.12603+004	-.34870+004	.97227+000	-.16047+000	.21903-009	.20363-009	.87738-006	-.65132-006	200
.32080+003	.10689+004	-.32930+004	.96461+000	-.18844+000	.21212-009	.11994-009	.49223-006	-.66728-006	220
.35010+003	.90149+003	-.31127+004	.95610+000	-.21496+000	.18165-009	.57516-010	.21734-006	-.56474-006	240
.37939+003	.75577+003	-.29441+004	.94680+000	-.24026+000	.14337-009	.22180-010	.67033-007	-.42550-006	260
.40869+003	.62942+003	-.27857+004	.93677+000	-.26447+000	.11186-009	.54685-011	-.12741-008	-.31133-006	280
.43799+003	.52030+003	-.26367+004	.92606+000	-.28770+000	.88601-010	-.30121-011	-.32324-007	-.22877-006	300
.46729+003	.42641+003	-.24965+004	.91469+000	-.31001+000	.70248-010	-.82549-011	-.46911-007	-.16653-006	320
.49658+003	.34592+003	-.23649+004	.90272+000	-.33146+000	.54991-010	-.11074-010	-.50844-007	-.11848-006	340
.52588+003	.27717+003	-.22412+004	.89018+000	-.35208+000	.42619-010	-.11378-010	-.46926-007	-.83017-007	360
.55518+003	.21870+003	-.21253+004	.87711+000	-.37190+000	.32721-010	-.10189-010	-.39407-007	-.57558-007	380
.58447+003	.16916+003	-.20166+004	.86353+000	-.39094+000	.24794-010	-.83747-011	-.31063-007	-.39437-007	400
.61377+003	.12742+003	-.19149+004	.84948+000	-.40920+000	.18570-010	-.63223-011	-.23156-007	-.26907-007	420
.64307+003	.92425+002	-.18197+004	.83500+000	-.42672+000	.13879-010	-.42639-011	-.16353-007	-.18654-007	440
.67236+003	.63294+002	-.17307+004	.82011+000	-.44348+000	.10506-010	-.23441-011	-.10912-007	-.13530-007	460
.70166+003	.39238+002	-.16475+004	.80486+000	-.45950+000	.81101-011	-.68105-012	-.67988-008	-.10406-007	480
.73096+003	.19570+002	-.15698+004	.78928+000	-.47478+000	.63623-011	.67598-012	-.37997-008	-.84353-008	500
.76025+003	.36917+001	-.14972+004	.77339+000	-.48933+000	.50545-011	.16760-011	-.17448-008	-.70848-008	520
.78955+003	-.89203+001	-.14293+004	.75723+000	-.50316+000	.40453-011	.24040-011	-.34551-009	-.61054-008	540
.81885+003	-.18722+002	-.13660+004	.74083+000	-.51627+000	.31714-011	.29636-011	.68993-009	-.53098-008	560
.84814+003	-.26110+002	-.13069+004	.72423+000	-.52867+000	.24157-011	.33879-011	.14450-008	-.46578-008	580
.87744+003	-.31431+002	-.12517+004	.70744+000	-.54037+000	.18293-011	.37230-011	.19555-008	-.41896-008	600
.90674+003	-.34987+002	-.12001+004	.69051+000	-.55137+000	.13660-011	.39781-011	.22829-008	-.38341-008	620
.93604+003	-.37041+002	-.11520+004	.67346+000	-.56169+000	.98320-012	.41374-011	.24630-008	-.35226-008	640
.96533+003	-.37824+002	-.11070+004	.65632+000	-.57132+000	.66238-012	.42367-011	.25513-008	-.32517-008	660
.99463+003	-.37535+002	-.10650+004	.63912+000	-.58030+000	.39062-012	.42905-011	.25762-008	-.30120-008	680
.10239+004	-.36348+002	-.10258+004	.62188+000	-.58861+000	.16508-012	.42912-011	.25423-008	-.27898-008	700
.10532+004	-.34416+002	-.98919+003	.60462+000	-.59629+000	-.33853-013	.42445-011	.24722-008	-.25724-008	720

.10825+004	-.31870+002	-.95497+003	.58738+000	-.60333+000	-.22787-012	.41655-011	.23920-008	-.23545-008	740
.11118+004	-.28826+002	-.92299+003	.57018+000	-.60976+000	-.41862-012	.40827-011	.23193-008	-.21519-008	760
.11411+004	-.25383+002	-.89309+003	.55303+000	-.61558+000	-.60079-012	.40076-011	.22555-008	-.19722-008	780
.11704+004	-.21628+002	-.86515+003	.53596+000	-.62082+000	-.76183-012	.39294-011	.21873-008	-.18130-008	800
.11997+004	-.17636+002	-.83902+003	.51899+000	-.62548+000	-.91105-012	.38602-011	.21248-008	-.16745-008	820
.12290+004	-.13473+002	-.81458+003	.50214+000	-.62959+000	-.10627-011	.38176-011	.20813-008	-.15580-008	840
.12583+004	-.91953+001	-.79171+003	.48543+000	-.63315+000	-.11830-011	.37940-011	.20343-008	-.14710-008	860
.12876+004	-.48505+001	-.77032+003	.46886+000	-.63619+000	-.12466-011	.37656-011	.19622-008	-.14076-008	880
.13169+004	-.48069+000	-.75029+003	.45247+000	-.63873+000	-.12710-011	.36900-011	.18609-008	-.13381-008	900
.13462+004	.38784+001	-.73154+003	.43626+000	-.64077+000	-.12836-011	.36192-011	.17635-008	-.12775-008	920
.13755+004	.81962+001	-.71399+003	.42024+000	-.64233+000	-.13091-011	.36494-011	.17101-008	-.12614-008	940
.14048+004	.12447+002	-.69754+003	.40443+000	-.64344+000	-.13125-011	.36700-011	.16472-008	-.12480-008	960
.14341+004	.16609+002	-.68212+003	.38884+000	-.64411+000	-.12619-011	.35676-011	.15307-008	-.11962-008	980
.14634+004	.20664+002	-.66767+003	.37348+000	-.64435+000	-.11964-011	.34298-011	.14064-008	-.11348-008	1000
.14927+004	.24596+002	-.65412+003	.35837+000	-.64419+000	-.11377-011	.33038-011	.12962-008	-.10783-008	1020
.15220+004	.28393+002	-.64141+003	.34349+000	-.64364+000	-.10804-011	.31642-011	.11905-008	-.10177-008	1040
.15513+004	.32045+002	-.62948+003	.32888+000	-.64272+000	-.10238-011	.30127-011	.10892-008	-.95409-009	1060
.15806+004	.35544+002	-.61827+003	.31453+000	-.64144+000	-.96960-012	.28617-011	.99543-009	-.89225-009	1080
.16099+004	.38884+002	-.60775+003	.30044+000	-.63983+000	-.91858-012	.27131-011	.90936-009	-.83273-009	1100
.16392+004	.42060+002	-.59786+003	.28663+000	-.63789+000	-.87119-012	.25669-011	.83048-009	-.77532-009	1120
.16685+004	.45068+002	-.58857+003	.27309+000	-.63564+000	-.82776-012	.24230-011	.75836-009	-.71989-009	1140
.16978+004	.47907+002	-.57982+003	.25984+000	-.63311+000	-.78855-012	.22814-011	.69255-009	-.66635-009	1160
.17271+004	.50575+002	-.57159+003	.24687+000	-.63030+000	-.75368-012	.21421-011	.63267-009	-.61461-009	1180
.17563+004	.53073+002	-.56384+003	.23418+000	-.62723+000	-.72319-012	.20052-011	.57829-009	-.56467-009	1200
.17856+004	.55400+002	-.55653+003	.22178+000	-.62391+000	-.69693-012	.18708-011	.52903-009	-.51650-009	1220
.18149+004	.57559+002	-.54964+003	.20967+000	-.62037+000	-.67490-012	.17390-011	.48449-009	-.47011-009	1240
.18442+004	.59551+002	-.54313+003	.19784+000	-.61661+000	-.65661-012	.16099-011	.44427-009	-.42553-009	1260
.18735+004	.61379+002	-.53699+003	.18631+000	-.61264+000	-.64174-012	.14836-011	.40800-009	-.38277-009	1280
.19028+004	.63044+002	-.53119+003	.17506+000	-.60848+000	-.62981-012	.13601-011	.37526-009	-.34187-009	1300
.19321+004	.64551+002	-.52569+003	.16410+000	-.60415+000	-.62024-012	.12395-011	.34568-009	-.30285-009	1320
.19614+004	.65902+002	-.52049+003	.15342+000	-.59965+000	-.61240-012	.11219-011	.31887-009	-.26573-009	1340
.19907+004	.67102+002	-.51556+003	.14302+000	-.59500+000	-.60560-012	.10074-011	.29446-009	-.23053-009	1360
.20200+004	.68153+002	-.51088+003	.13291+000	-.59021+000	-.59906-012	.89597-012	.27208-009	-.19727-009	1380
.20493+004	.69061+002	-.50644+003	.12307+000	-.58529+000	-.59174-012	.78811-012	.25135-009	-.16611-009	1400
.20786+004	.69829+002	-.50222+003	.11350+000	-.58025+000	-.58261-012	.68439-012	.23190-009	-.13720-009	1420
.21079+004	.70461+002	-.49820+003	.10421+000	-.57510+000	-.57087-012	.58537-012	.21348-009	-.11065-009	1440
.21372+004	.70961+002	-.49436+003	.95187-001	-.56985+000	-.55596-012	.49159-012	.19588-009	-.86522-010	1460
.21665+004	.71334+002	-.49070+003	.86427-001	-.56451+000	-.53754-012	.40352-012	.17895-009	-.64848-010	1480
.21958+004	.71585+002	-.48721+003	.77928-001	-.55909+000	-.51547-012	.32162-012	.16262-009	-.45613-010	1500
.22251+004	.71717+002	-.48386+003	.69684-001	-.55360+000	-.48983-012	.24628-012	.14684-009	-.28776-010	1520
.22544+004	.71734+002	-.48066+003	.61693-001	-.54805+000	-.46085-012	.17781-012	.13162-009	-.14268-010	1540
.22837+004	.71642+002	-.47758+003	.53950-001	-.54244+000	-.42892-012	.11644-012	.11698-009	-.19953-011	1560
.23130+004	.71444+002	-.47462+003	.46450-001	-.53678+000	-.39455-012	.62326-013	.10297-009	.81574-011	1580
.23423+004	.71144+002	-.47177+003	.39188-001	-.53108+000	-.35834-012	.15493-013	.89654-010	.16326-010	1600
.23716+004	.70747+002	-.46902+003	.32161-001	-.52535+000	-.32094-012	-.24132-013	.77088-010	.22660-010	1620
.24009+004	.70256+002	-.46637+003	.25363-001	-.51959+000	-.28303-012	-.56736-013	.65337-010	.27327-010	1640
.24302+004	.69675+002	-.46380+003	.18790-001	-.51381+000	-.24530-012	-.82613-013	.54458-010	.30498-010	1660
.24595+004	.69010+002	-.46132+003	.12436-001	-.50801+000	-.20840-012	-.10216-012	.44493-010	.32356-010	1680
.24888+004	.68262+002	-.45890+003	.62971-002	-.50220+000	-.17294-012	-.11587-012	.35474-010	.33081-010	1700
.25181+004	.67437+002	-.45656+003	.36835-003	-.49639+000	.00000	.00000	.00000	.00000	1720
.25474+004	.66537+002	-.45427+003	-.53553-002	-.49058+000	.00000	.00000	.00000	.00000	1740
.25767+004	.65567+002	-.45204+003	-.10879-001	-.48477+000	.00000	.00000	.00000	.00000	1760
.26060+004	.64530+002	-.44986+003	-.16206-001	-.47898+000	.00000	.00000	.00000	.00000	1780
.26353+004	.63429+002	-.44773+003	-.21344-001	-.47319+000	.00000	.00000	.00000	.00000	1800
.26646+004	.62267+002	-.44564+003	-.26295-001	-.46743+000	.00000	.00000	.00000	.00000	1820
.26938+004	.61049+002	-.44359+003	-.31065-001	-.46168+000	.00000	.00000	.00000	.00000	1840
.27231+004	.59776+002	-.44157+003	-.35659-001	-.45596+000	.00000	.00000	.00000	.00000	1860

.27524+004	.58453+002	-.43958+003	-.40081-001	-.45026+000	.00000	.00000	.00000	.00000	1880
.27817+004	.57082+002	-.43763+003	-.44336-001	-.44460+000	.00000	.00000	.00000	.00000	1900
.28110+004	.55665+002	-.43569+003	-.48429-001	-.43897+000	.00000	.00000	.00000	.00000	1920
.28403+004	.54206+002	-.43378+003	-.52363-001	-.43337+000	.00000	.00000	.00000	.00000	1940
.28696+004	.52708+002	-.43189+003	-.56143-001	-.42781+000	.00000	.00000	.00000	.00000	1960
.28989+004	.51173+002	-.43002+003	-.59775-001	-.42230+000	.00000	.00000	.00000	.00000	1980
.29282+004	.49603+002	-.42816+003	-.63261-001	-.41682+000	.00000	.00000	.00000	.00000	2000
.29575+004	.48002+002	-.42631+003	-.66606-001	-.41139+000	.00000	.00000	.00000	.00000	2020
.29868+004	.46371+002	-.42448+003	-.69815-001	-.40600+000	.00000	.00000	.00000	.00000	2040

TIME (SECONDS)	RE(FFT)	IM(FFT)	G(RHO,T)-V/M
.00000	-.45781-005	.34959-003	-.91562-005
.33333-003	-.68935-004	.47414-003	-.13787-003
.66667-003	-.22306-003	.58384-003	-.44613-003
.10000-002	-.45688-003	.61742-003	-.91376-003
.13333-002	-.71019-003	.52672-003	-.14204-002
.16667-002	-.90537-003	.32022-003	-.18107-002
.20000-002	-.99158-003	.51787-004	-.19832-002
.23333-002	-.96391-003	-.21258-003	-.19278-002
.26667-002	-.85123-003	-.42579-003	-.17025-002
.30000-002	-.69399-003	-.56785-003	-.13880-002
.33333-002	-.52830-003	-.64134-003	-.10566-002
.36667-002	-.37834-003	-.66127-003	-.75667-003
.40000-002	-.25609-003	-.64687-003	-.51218-003
.43333-002	-.16331-003	-.61610-003	-.32663-003
.46667-002	-.94654-004	-.58223-003	-.18331-003
.50000-002	-.41574-004	-.55199-003	-.83148-004
.53333-002	.37299-005	-.52636-003	.74597-005
.56667-002	.46132-004	-.50286-003	.92265-004
.60000-002	.87080-004	-.47816-003	.17416-003
.63333-002	.12560-003	-.44988-003	.25121-003
.13000-001	.19411-003	-.24766-004	.38822-003
.19667-001	.87455-004	.58464-004	.17491-003
.26333-001	.19347-004	.56813-004	.38694-004
.33000-001	-.53266-005	.35412-004	-.10653-004
.39667-001	-.15415-004	.17887-004	-.30831-004
.46333-001	-.14558-004	.15268-005	-.29117-004
.53000-001	-.65226-005	-.70893-005	-.13046-004
.59667-001	.23616-005	-.84114-005	.47233-005
.66333-001	.83480-005	-.47353-005	.16696-004
.73000-001	.10208-004	.57895-006	.20416-004
.79667-001	.88593-005	.50039-005	.17719-004
.86333-001	.60065-005	.73361-005	.12013-004
.93000-001	.32645-005	.79147-005	.65290-005
.99667-001	.11739-005	.75681-005	.23479-005
.10633+000	-.27174-006	.68955-005	-.54347-006
.11300+000	-.13046-005	.62047-005	-.26091-005
.11967+000	-.21326-005	.55378-005	-.42652-005
.12633+000	-.28506-005	.48518-005	-.57013-005
.13300+000	-.34611-005	.40355-005	-.69221-005
.13967+000	-.39522-005	.32563-005	-.79044-005
.14633+000	-.42716-005	.23187-005	-.85431-005
.15300+000	-.43552-005	.13408-005	-.87105-005
.15967+000	-.41928-005	.41483-006	-.83855-005
.16633+000	-.38271-005	-.37260-006	-.76543-005
.17300+000	-.33397-005	-.97705-006	-.66794-005
.17967+000	-.28070-005	-.14031-005	-.56140-005
.18633+000	-.22776-005	-.16869-005	-.45553-005
.19300+000	-.17645-005	-.18566-005	-.35290-005
.19967+000	-.12786-005	-.19274-005	-.25572-005
.20633+000	-.83040-006	-.19116-005	-.16608-005
.21300+000	-.43165-006	-.18210-005	-.86330-006
.21967+000	-.92376-007	-.16722-005	-.18475-006
.22633+000	.18198-006	-.14825-005	.36396-006
.23300+000	.39142-006	-.12691-005	.78284-006
.23967+000	.53774-006	-.10475-005	.10755-005

.24633+000	.62846-006	-.83367-006	.12569-005
.25300+000	.67621-006	-.63649-006	.13524-005
.25967+000	.69220-006	-.45869-006	.13844-005
.26633+000	.68404-006	-.29899-006	.13681-005
.27300+000	.65539-006	-.15616-006	.13108-005
.27967+000	.60849-006	-.31000-007	.12170-005
.28633+000	.54641-006	.73916-007	.10928-005
.29300+000	.47486-006	.15766-006	.94971-006
.29967+000	.39841-006	.22117-006	.79681-006
.30633+000	.32073-006	.26628-006	.64146-006
.31300+000	.24448-006	.29525-006	.48897-006
.31967+000	.17137-006	.31000-006	.34273-006
.32633+000	.10244-006	.31217-006	.20487-006
.33300+000	.39165-007	.30296-006	.78330-007
.33967+000	-.17301-007	.28373-006	-.34601-007
.34633+000	-.65488-007	.25579-006	-.13098-006
.35300+000	-.10382-006	.22144-006	-.20764-006
.35967+000	-.13182-006	.18339-006	-.26363-006
.36633+000	-.15010-006	.14418-006	-.30021-006
.37300+000	-.15947-006	.10550-006	-.31894-006
.37967+000	-.16090-006	.68796-007	-.32180-006
.38633+000	-.15543-006	.35080-007	-.31086-006
.39300+000	-.14378-006	.54640-008	-.28756-006
.39967+000	-.12721-006	-.19079-007	-.25442-006
.40633+000	-.10708-006	-.37768-007	-.21417-006
.41300+000	-.84885-007	-.50113-007	-.16977-006
.41967+000	-.62452-007	-.55782-007	-.12490-006
.42633+000	-.42114-007	-.55536-007	-.84228-007
.43300+000	-.25053-007	-.51080-007	-.50105-007
.43967+000	-.11636-007	-.44101-007	-.23273-007
.44633+000	-.14352-008	-.35812-007	-.28704-008
.45300+000	.59680-008	-.26478-007	.11936-007
.45967+000	.10251-007	-.16422-007	.20502-007
.46633+000	.10667-007	-.66543-008	.21333-007
.47300+000	.79109-008	.90841-009	.15822-007
.47967+000	.34178-008	.54885-008	.68356-008
.48633+000	-.13507-008	.68868-008	-.27014-008
.49300+000	-.49895-008	.57393-008	-.99790-008
.49967+000	-.68399-008	.28674-008	-.13680-007
.50633+000	-.62835-008	-.72570-009	-.12567-007
.51300+000	-.30785-008	-.37954-008	-.61570-008
.51967+000	.20571-008	-.42835-008	.41143-008
.52633+000	.65274-008	-.19283-008	.13055-007
.53300+000	.91805-008	.17737-008	.18361-007
.53967+000	.10147-007	.53283-008	.20293-007
.54633+000	.10803-007	.81544-008	.21606-007
.55300+000	.11864-007	.11699-007	.23728-007
.55967+000	.11983-007	.17123-007	.23966-007
.56633+000	.82090-008	.23445-007	.16418-007
.57300+000	.98146-009	.26745-007	.19629-008
.57967+000	-.71908-008	.25821-007	-.14382-007
.58633+000	-.13800-007	.20651-007	-.27601-007
.59300+000	-.16868-007	.13197-007	-.33737-007
.59967+000	-.16652-007	.50581-008	-.33303-007
.60633+000	-.12655-007	-.29556-008	-.25310-007
.61300+000	-.37648-008	-.97916-008	-.75296-008
.61967+000	.10200-007	-.92448-008	.20401-007

.62633+000	.20896-007	.95583-009	.41791-007
.63300+000	.22444-007	.16386-007	.44888-007
.63967+000	.11749-007	.29031-007	.23497-007
.64633+000	-.46412-008	.28345-007	-.92823-008
.65300+000	-.13730-007	.15975-007	-.27460-007
.65967+000	-.65535-008	.27811-008	-.13107-007
.66633+000	.92403-009	.59037-008	.18481-008
.67300+000	.26998-009	.53380-008	.53996-009
.67967+000	.13608-011	.18206-008	.27216-011

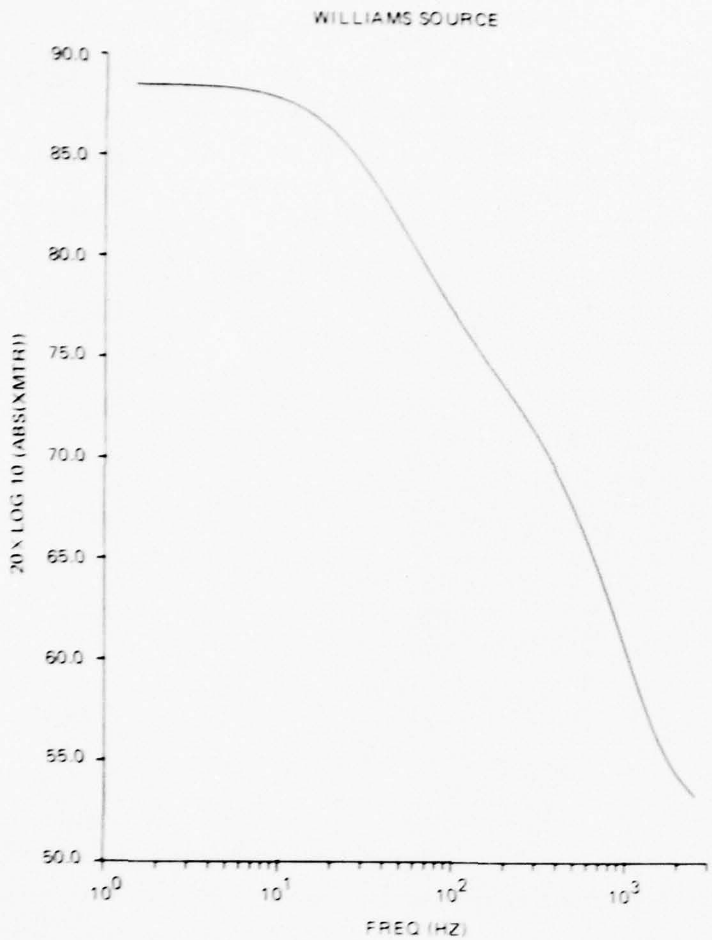

Figure 1. Transmitter spectrum.

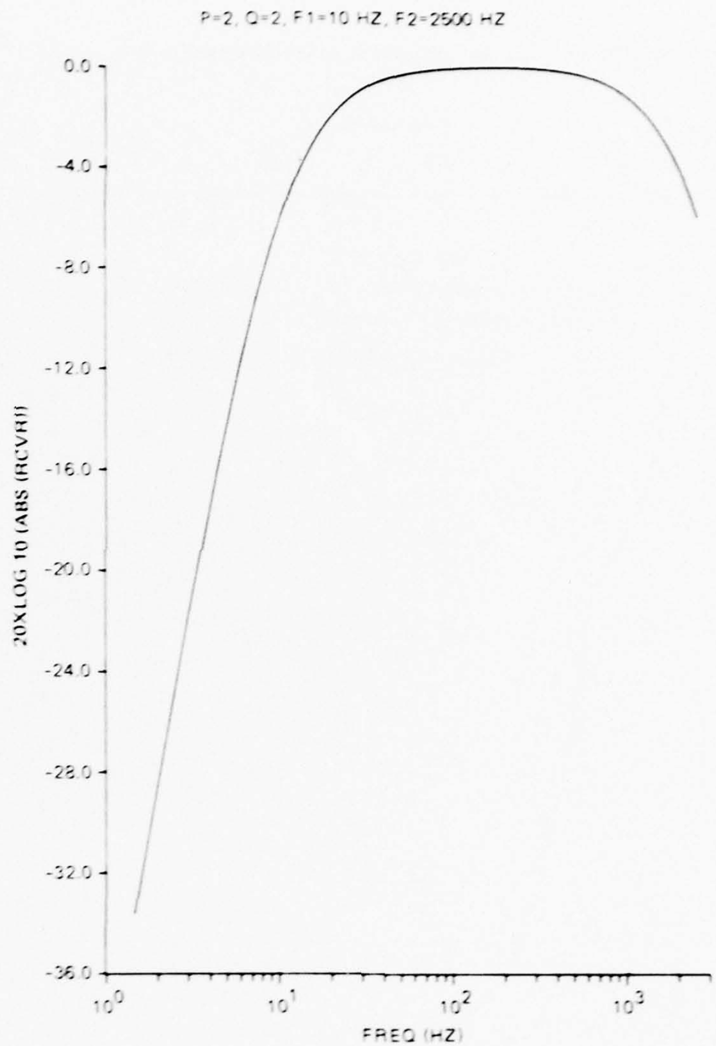

Figure 2. Receiver spectrum.

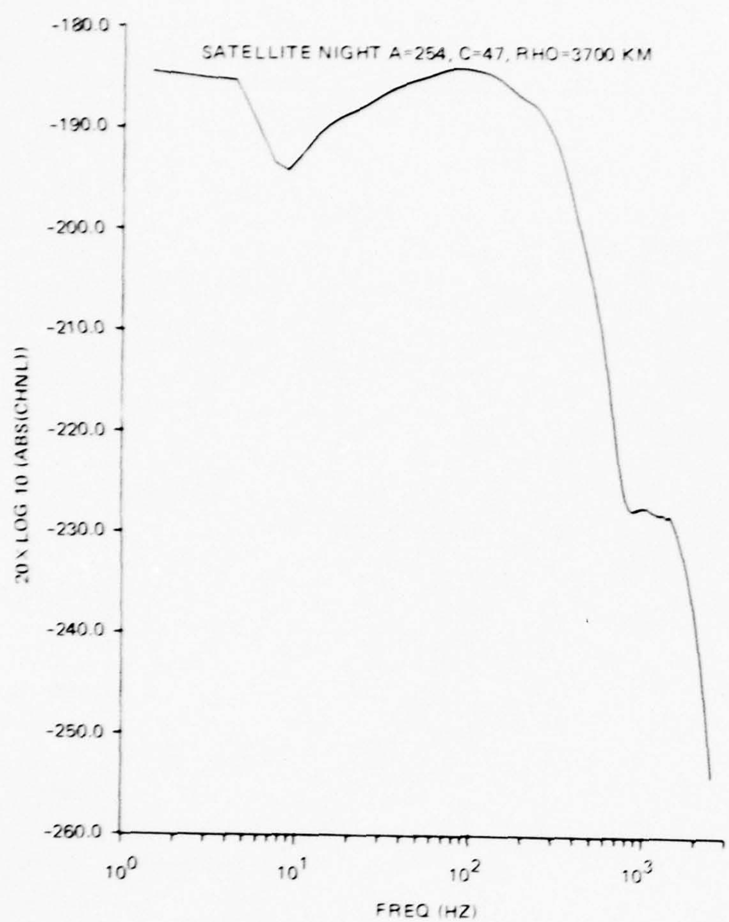

Figure 3. Channel spectrum.

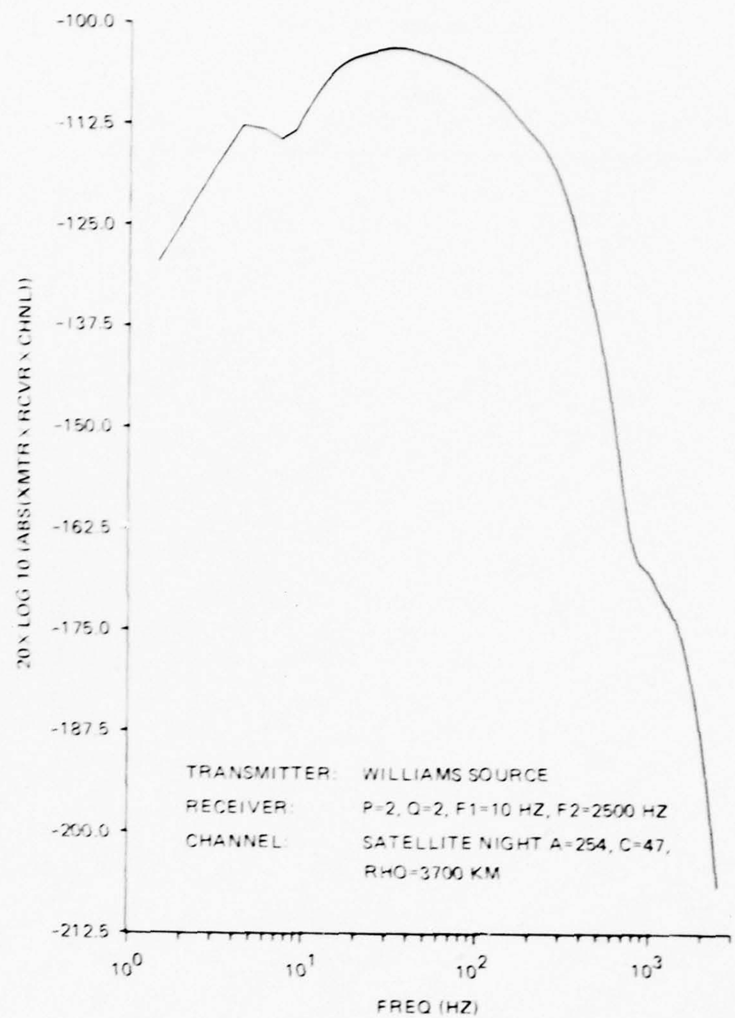

Figure 4. Product spectrum of transmitter, receiver and channel.

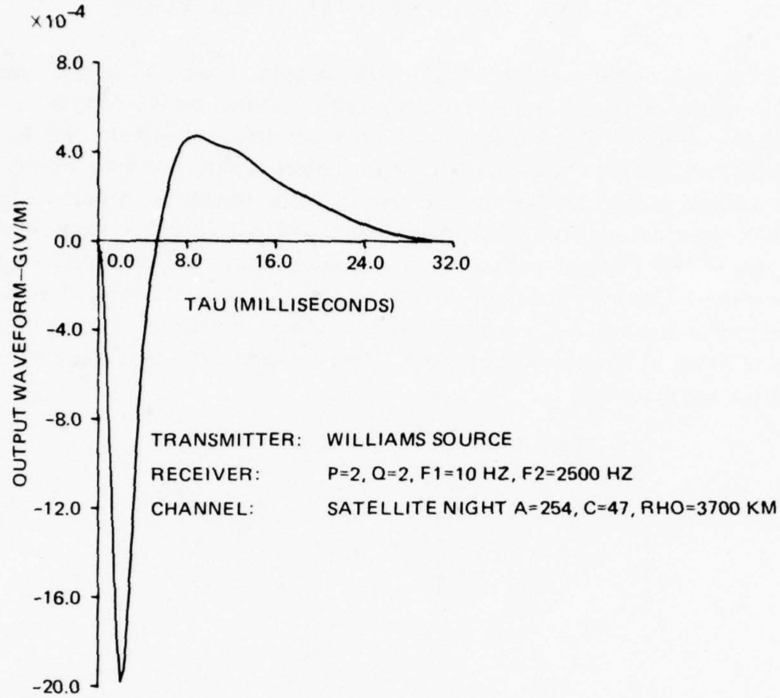

Figure 5. Output waveform.

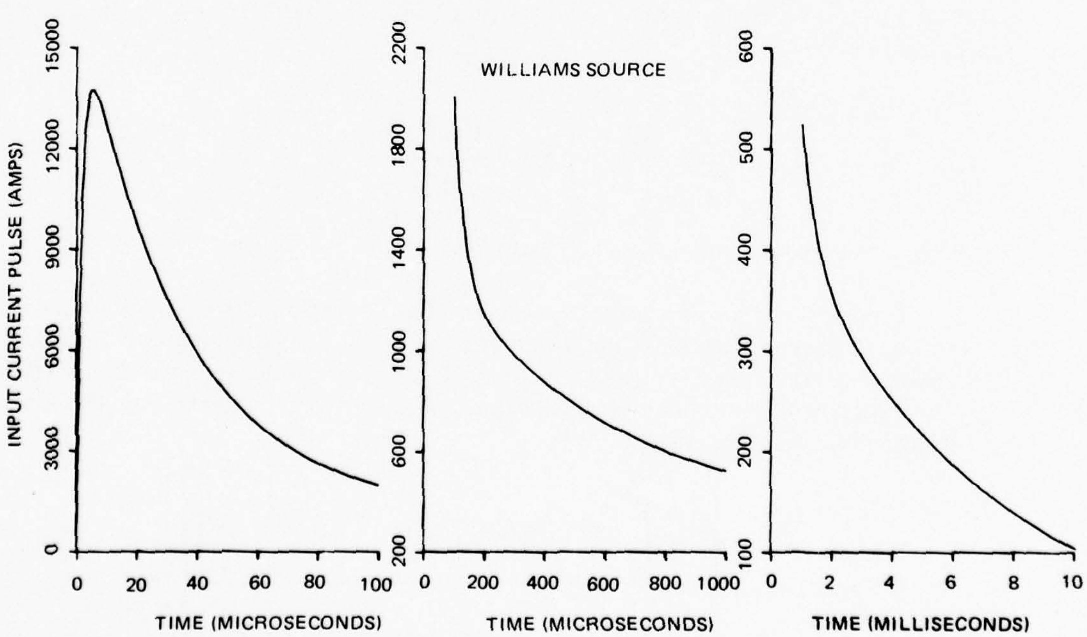

Figure 6. Input current pulse.

VI. AN ADDITIONAL APPLICATION

As an additional example of the problem type to which the present program may be applied we consider a case study similar to that examined by Rothmuller (Ref. 5) in his report on the effect of the propagation channel on spread-spectrum communication systems. Rothmuller investigated the effect that propagation at very low frequencies (vlf) through the earth-ionosphere waveguide has on one type of communication system. The system studied was characterized by a differential phase-encoded signal waveform composed by frequency shift keying (FSK) a carrier with a binary pseudo-random or pseudo-noise (PN) sequence of pulses or chips. The FSK modulation index is 0.5, which is designated as minimum shift keying (MSK). For more detail concerning the basic waveform and terminology the interested reader is referred to Rothmuller's report. Here we note only that the PN sequence has a power spectrum given by

$$P(F) = P_o \frac{\cos^2\left[\frac{F - F_o}{F_c} 2\pi\right]}{\left[1 - 16\left(\frac{F - F_o}{F_c}\right)^2\right]^2} \quad ; P_o = \frac{16}{\pi^2 F_c} \qquad (20)$$

where

F_o is the carrier frequency

F_c is the chip frequency.

The communication system to be evaluated is assumed to consist in part of a receiver followed by a demodulator matched to the undistorted transmitter signal. The receiver response modeled by

$$R(F) = \frac{1}{\left[1 + j\frac{F - F_o}{F_1}\right]^3} + \frac{1}{\left[1 - j\frac{F + F_o}{F_1}\right]^3} \quad ; F_1 = 1 \text{ kHz} \qquad (21)$$

will be assumed in the subsequent calculations.

Figure 7 shows a vlf waveguide signal plot as a function of frequency for a daytime Hawaii to southern California propagation direction and for a path length of 2282 km. Observe the deep null at 23.5 kHz. One possible measure of relative performance (RP) of a spread spectrum system operating at a carrier frequency F_o = 23.5 kHz, over the same system operating at the single frequency F_o is

$$RP = 10\text{Log}_{10} \frac{\left[R_e\left\{\int_0^{\infty} P(F)R(F)H(F,\rho)\, e^{2\pi j(F-F_o)\tau}\, dF\right\}\right]^2}{\left[R_e\left\{H(F_o,\rho)\int_0^{\infty} P(F)R(F)\, e^{2\pi j(F-F_o)\tau}\, dF\right\}\right]^2_{max}} \qquad (22)$$

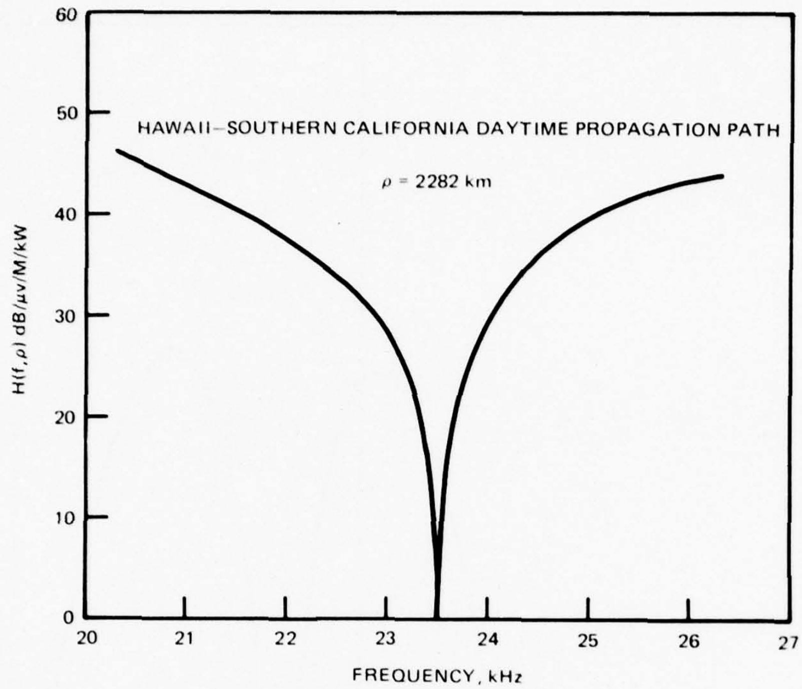

Figure 7. Daytime mode sum as a function of frequency.

where the subscript "max" signifies the maximum value of the squared denominator. The Fourier integrals in Eq. (22) can be evaluated using the present program and results are shown in Fig. 8 for chip frequencies of 100 sec^{-1} and 1000 sec^{-1}. It will be seen that two correlation peaks occur. This phenomenon has been discussed by Rothmuller. A relative performance of 20 dB could be expected for the case of F_c = 1000 sec^{-1} and about 4.5 dB for the system operating at F_c = 100 sec^{-1}. Of course, if the system were operating at a central frequency, F_0, corresponding to a maximum in the mode sum, the relative performance would be degraded. Generally, though, the gain in performance in the neighborhood of nulls would outweigh the loss of performance in the neighborhood of maxima.

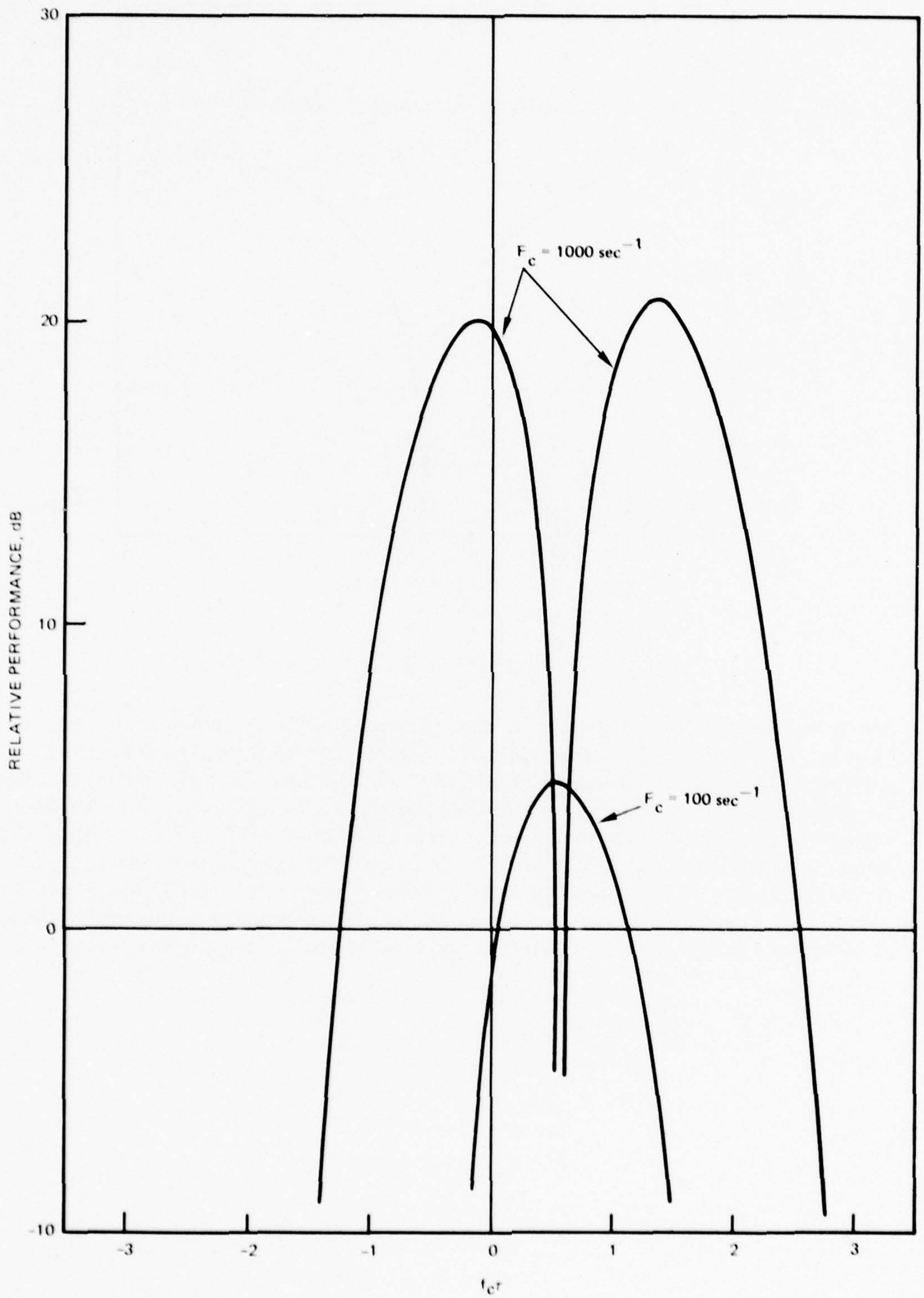

Figure 8. Relative performance of spread-spectrum system.

REFERENCES

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2. C. E. Seyler, Jr., S. C. Bloch and R. W. Flynn, "Pulse Propagation in a Magnetoplasma 1. Longitudinal Propagation," J. Geophys. Res., 77(22), pp. 4237–4241, 1972.

3. J. Galejs, "Terrestrial Propagation of Long Electromagnetic Waves," Pergammon Press, NY, 1972.

4. J. W. Cooley and J. W. Tukey, "An Algorithm for the Machine Calculation of Complex Fourier Series," Math. Comput., 19, 297–301, 1965.

5. I. J. Rothmuller, "Effects of the VLF Propagation Channel on Spread-Spectrum Communication Systems," Naval Electronics Laboratory Center TN 1834, 1972.

APPENDIX

```
      IMPLICIT REAL*8(A-H,O-Z)
      COMPLEX*16 TEMPF,TEMPL,GB
       COMPLEX*16 XMTR,RCVR,CHNL,FOFTAU
       COMPLEX*16 IM/(0.0D0,1.0D0)/
      REAL*8 IT
      REAL*8 IMTHP
      REAL*4 PLOTX(3000),PLOTY1(3000),PLOTY2(3000),PLOTY3(3000)
      REAL*4 PLOTY4(3000)
      INTEGER P,Q
      COMMON/ONE/XMTR
      COMMON/TWO/RCVR
      COMMON/THREE/CHNL
      COMMON/FOUR/A(4),GAM(4),TAUP,TAUV,VO
      COMMON/FIVE/GA,OMEGA1,OMEGA2,P,Q
      COMMON/SIX/MODE(15,50)
      COMMON/SEVEN/FREQ(50),XTRMAG(15,50),XTRANG(15,50),RETHP(15,50),
     $  IMTHP(15,50),ATT(15,50),PHVOC(15,50),NFVF,NF,NM
      COMMON/NINE/RHO
      COMMON/ELEVEN/KK(15)
      DIMENSION TMIN(3),TINC(3),NUMTS(3)
      DIMENSION XX(50),YY(50),B(50),C(50),D(50)
      DIMENSION NEVF(6),X(2049),Y(2049)
      DIMENSION LABELT(10),LABELR(10),LABELC(10)
      NAMELIST/DATUM/A,GAM,TAUP,TAUV,VO,GA,OMEGA1,OMEGA2,P,Q,NM,NEVF,N,
     $  FU,FL,NF,RHO,S,INTPRT,IPLOT,TAUMAX
     $  ,TMIN,TINC,NUMTS
      DATA PI/3.14159265358979324D0/
C
      READ(5,901) LABELT
      PRINT 902,LABELT
      READ(5,901) LABELR
      PRINT 903,LABELR
      READ(5,901) LABELC
      PRINT 904,LABELC
      READ(5,DATUM)
      WRITE(6,DATUM)
      TWOPI = PI*2.0D0
      DTR = PI/1.80D2
      DO 25 KF=1,NF
      DO 25 M=1,NM
25    MODE(M,KF)=0
      PRINT 920
      DO 92 KF=1,NF
      M=0
      NMS=0
 91   M=M+1
      READ(5,11) NMF,RETHP(M,KF),IMTHP(M,KF),XTRMAG(M,KF),XTRANG(M,KF),
     $  FREQ(KF),ATT(M,KF),PHVOC(M,KF)
      WRITE(6,12) NMF,FREQ(KF),RETHP(M,KF),IMTHP(M,KF),XTRMAG(M,KF),
     $  XTRANG(M,KF),ATT(M,KF),PHVOC(M,KF)
      IF (NMF .NE. 0) NMS=NMF
      IF(NMS . EQ. 0) NMS=NM
       RETHP(M,KF)=RETHP(M,KF)*DTR
      IMTHP(M,KF)=IMTHP(M,KF)*DTR
```

```
      MODE(M,KF)=M
      IF(M .LT. NMS) GOTO91
92    FREQ(KF)=FREQ(KF)*1000.D0
      FL=FL*1000.D0
      FU=FU*1000.D0
      DO 76 M=1,NM
      KMODE = 0
      KMODE1 = 1
      DO 71 KF =1,NF
71    IF(MODE(M,KF) .NE. 0) KMODE=KMODE+1
      DO 74 KF=1,NF
74    IF(MODE(M,KF) .NE. 0) MODE(M,KF)=KMODE
      DO 75 KF=1,NF
      IF(MODE(M,KF) .EQ. 0) KMODE1=KMODE1+1
      KK(M) = KMODE1
75    IF(MODE(M,KF) .NE. 0) GO TO 76
76    CONTINUE
      DO 65 MD=1,NM
      LF=0
      L=0
50     L=L+1
      NEVF=L
51     IF (NEVF(L)  .EQ. 1) GO TO 59
      LF=LF+1
      CALL FUNSPL (MD,LF,XX,YY,B,C,D)
59     IF(L .LT. 6) GO TO 50
65     CONTINUE
      NN=0
      NP=2**N
      NP1=NP+1
      DLT = (FU-FL)/NP
      PRINT 915
      NUMPTS = 0
      DO 10 K=1,NP1
      F=(K-1)*(FU-FL)/NP+FL
      CALL TRXMTR (F)
      CALL RECVR(F)
      CALL CHANEL (F)
      X(K)= XMTR*RCVR*CHNL
      Y(K)= -IM*XMTR*RCVR*CHNL
      IF(F .LT. FREQ(1) .OR. F .GT. FREQ(NF)) GO TO 68
      NUMPTS = NUMPTS+1
      PLOTX(NUMPTS) = F
      PLOTY1(NUMPTS) = 20.0*DLOG10(CDABS(XMTR))
      PLOTY2(NUMPTS) = 20.0*DLOG10(CDABS(RCVR))
      PLOTY3(NUMPTS) = 20.0*DLOG10(CDABS(CHNL))
      PLOTY4(NUMPTS) = 20.0*DLOG10(DSQRT(X(K)**2+Y(K)**2))
68    IF(K .GE. 20 .AND. MOD(K,INTPRT) .NE. 0) GO TO 10
      PRINT 900,F,XMTR,RCVR,CHNL,X(K),Y(K),K
10    CONTINUE
      IF(IPLOT    .EQ. 0) GO TO 250
      CALL INK('PEN 2 = BLACK$')
      CALL BGNPL(1)
      CALL OPNPLT
      CALL XLABEL('FREQ(HZ)',8)
      CALL YLABEL('20*LOG10(ABS(XMTR))',19)
      CALL XLGPLT(PLOTX,PLOTY1,NUMPTS)
```

```
      CALL MESSAG('TRANSMITTER SPECTRUM:',21,2.0,8.5)
      CALL MESSAG( LABELT ,40,2.0,8.3)
      CALL ENDPL(0)
      CALL BGNPL(2)
      CALL OPNPLT
      CALL XLABEL('FREQ(HZ)',8)
      CALL YLABEL('20*LOG10(ABS(RCVR))',19)
      CALL XLGPLT(PLOTX,PLOTY2,NUMPTS)
      CALL MESSAG('RECEIVER SPECTRUM:',18,1.0,9.6)
      CALL MESSAG(LABELR,40,1.0,9.4)
      CALL ENDPL(0)
      CALL BGNPL(3)
      CALL OPNPLT
      CALL XLABEL('FREQ(HZ)',8)
      CALL YLABEL('20*LOG10(ABS(CHNL))',19)
      CALL XLGPLT(PLOTX,PLOTY3,NUMPTS)
      CALL MESSAG('CHANNEL SPECTRUM:',17,1.0,8.4)
      CALL MESSAG(LABELC,40,1.0,8.2)
      CALL ENDPL(0)
      CALL BGNPL(4)
      CALL OPNPLT
      CALL XLABEL('FREQ(HZ)',8)
      CALL YLABEL('20*LOG10(ABS(XMTR*RCVR*CHNL))',29)
      CALL XLGPLT(PLOTX,PLOTY4,NUMPTS)
      CALL MESSAG('PRODUCT SPECTRUM',16,0.5,10.0)
      CALL MESSAG('TRANSMITTER:',12,0.5,9.6)
      CALL MESSAG( LABELT ,40,2.0,9.6)
      CALL MESSAG('RECEIVER:',9,0.5,9.4)
      CALL MESSAG(LABELR,40,1.7,9.4)
      CALL MESSAG('CHANNEL:',8,0.5,9.2)
      CALL MESSAG(LABELC,40,1.6,9.2)
      CALL ENDPL(0)
250   CONTINUE
      TEMPF= X(1)+IM*Y(1)
      TEMPL = X(NP1)+IM*Y(NP1)
      CALL NLOGN(N,X,Y,S,FL,FU)
      PRINT 905
      NUMPTS=0
      DO 20 K=1,NP
      TAU=(K-1)/(FU-FL)
      OM = TWOPI*TAU
      IF(K .NE. 1) GO TO 2
      GB = DLT/2.0D0
      GO TO 3
2     GB = DLT/(S*IM*OM )+(1.0D0-CDEXP(-IM*S*OM *DLT))/(OM*OM)
      GB = GB/DLT
3     FOFTAU = CDEXP(IM*S*OM        *FL)*(X(K)+IM*Y(K)-TEMPF*GB+
     $ TEMPL*GB*CDEXP(IM*OM *S*(FU-FL)))
      RFOFT = 2.0D0*DREAL(FOFTAU)
      IF(TAU .GT. TAUMAX) GO TO 24
      NUMPTS = NUMPTS+1
      PLOTX(NUMPTS) = TAU*1.0E3
      PLOTY1(NUMPTS) = RFOFT
24    CONTINUE
      IF(K .GE. 20 .AND. MOD(K,INTPRT) .NE. 0) GO TO 20
      PRINT 910,TAU,FOFTAU,RFOFT
20    CONTINUE
```

```
      IF(IPLOT .EQ. 0) GO TO 260
      CALL BGNPL(5)
      CALL OPNPLT
      CALL XLABEL('TAU(MILLISECONDS)',17)
      CALL YLABEL('OUTPUT WAVEFORM-G(V/M)',22)
      CALL LINPLT(PLOTX,PLOTY1,NUMPTS)
      CALL MESSAG('OUTPUT WAVEFORM',15,0.0,8.8)
      CALL MESSAG('TRANSMITTER:',12,0.0,8.4)
      CALL MESSAG( LABELT ,40,1.5,8.4)
      CALL MESSAG('RECEIVER:',9,0.0,8.2)
      CALL MESSAG(LABELR,40,1.2,8.2)
      CALL MESSAG('CHANNEL:',8,0.0,8.0)
      CALL MESSAG(LABELC,40,1.1,8.0)
      CALL ENDPL(0)
      CALL BGNPL(6)
      CALL INTAXS
      T = TMIN(1)
      DO 45 J=1,NUMTS(1)
      IT = 0.0D0
      DO 40 K=1,4
      IT = IT+A(K)*DEXP(-T*GAM(K))
40    CONTINUE
      PLOTX(J) = T*1.0E6
      PLOTY1(J) = IT
      T = T+TINC(1)
45    CONTINUE
      CALL PHYSOR(0.8,2.0)
      CALL TITLE(' ',-1,'TIME(MICROSECONDS)',18,
     $  'INPUT CURRENT PULSE(AMPS)',25,3.0,5.0)
      CALL GRAF(0.,20.,100.,0.,3000.,15000.)
      CALL CURVE(PLOTX,PLOTY1,NUMTS(1),0)
      CALL ENDGR(0)
      T = TMIN(2)
      DO 46 J=1,NUMTS(2)
      IT = 0.0D0
      DO 41 K=1,4
      IT = IT+A(K)*DEXP(-T*GAM(K))
41    CONTINUE
      PLOTX(J) = T*1.0E6
      PLOTY1(J) = IT
      T = T+TINC(2)
46    CONTINUE
      CALL PHYSOR(4.25,2.0)
      CALL TITLE(' ',-1,'TIME(MICROSECONDS)',18,' ',1,3.0,5.0)
      CALL GRAF(0.,200.,1000.,200.,400.,2200.)
      CALL CURVE(PLOTX,PLOTY1,NUMTS(2),0)
      CALL MESSAG(LABELT,40,1.0,5.6)
      CALL ENDGR(0)
      T = TMIN(3)
      DO 47 J=1,NUMTS(3)
      IT = 0.0D0
      DO 42 K=1,4
      IT = IT+A(K)*DEXP(-T*GAM(K))
42    CONTINUE
      PLOTX(J) = T*1.0E3
      PLOTY1(J) = IT
      T = T+TINC(3)
```

```
47     CONTINUE
       CALL PHYSOR(7.70,2.0)
       CALL TITLE(' ',-1,'TIME(MILLISECONDS)',18,' ',1,3.0,5.0)
       CALL GRAF(0.,2.,10.,100.,100.,600.)
       CALL CURVE(PLOTX,PLOTY1,NUMTS(3),0)
       CALL ENDGR(0)
       CALL ENDPL(0)
260    CONTINUE
 11    FORMAT(I5,2F10.5,D15.6,4F10.5)
12     FORMAT(' ',25X,I5,3F10.5,D15.6,3F10.5)
900    FORMAT(' ',10X,9D12.5,I6)
901    FORMAT(10A4)
902    FORMAT('1',10A4)
903    FORMAT(' ',10A4)
904    FORMAT(' ',10A4,//)
905    FORMAT('1',46X,'TIME',7X,'RE(FFT)',5X,'IM(FFT)',4X,'G(RHO,T)-V/M',
      $  /,45X,'(SECONDS)')
910    FORMAT(' ',42X,4D12.5)
915    FORMAT('1',13X,'FREQ(HZ)',4X,'XMTR R',6X,'XMTR I',6X,'RCVR R',6X,
      $         'RCVR I',6X,'CHNL R',6X,'CHNL I',8X,'XMTR*RCVR*CHNL',
      $  10X,'K',/,' ',98X,'REAL',8X,'IMAG')
920    FORMAT('1',28X,'NMF',4X,'FREQ',3X,'THETAR',4X,'THETAI',7X,
      $  'XTRMAG',7X,'XTRANG',7X,'ATT',6X,'PHVOC',/,36X,'KHZ',4X,
      $  'DEGREES',3X,'DEGREES',19X,'RADIANS',6X,'DB')
999    RETURN
       END
```

```
      SUBROUTINE FUNSPL(MD,LF,XX,YY,B,C,D)
      IMPLICIT REAL*8(A-H,O-Z)
      REAL*8 IMTHP
      COMMON/SIX/MODE(15,50)
      COMMON/SEVEN/FREQ(50),XTRMAG(15,50),XTRANG(15,50),RETHP(15,50),
     $  IMTHP(15,50),ATT(15,50),PHVOC(15,50),NFVF,NF,NM
      COMMON/EIGHT/LM
      COMMON/TEN/YC(6,15,50),BC(6,15,50),CC(6,15,50),DC(6,15,50)
      DIMENSION XX(50)
      DIMENSION YY(50),
     $  B(50),C(50),D(50)
      CALL FUNCVF(MD,XX,YY)
      CALL SPLINE(XX,YY,B,C,D,LM)
      DO 46 I=1,NF
      YC(LF,MD,I)=YY(I)
      BC(LF,MD,I)=B(I)
      CC(LF,MD,I)=C(I)
      DC(LF,MD,I)=D(I)
46    CONTINUE
      RETURN
      END
```

```
      SUBROUTINE FUNCVF(MD,XX,YY)
      IMPLICIT REAL*8(A-H,O-Z)
      REAL*8 IMTHP
      COMMON/SIX/MODE(15,50)
      COMMON/SEVEN/FREQ(50),XTRMAG(15,50),XTRANG(15,50),RETHP(15,50),
     $ IMTHP(15,50),ATT(15,50),PHVOC(15,50),NFVF,NF,NM
      COMMON/EIGHT/LM
      COMMON/ELEVEN/KK(15)
      DIMENSION XX(50),YY(50)
      GO TO (30,40,50,60,70,80),NFVF
30    DO 35 I=1,NF
      IF(MODE(MD,I) .EQ. 0) GO TO 35
      JJ = I-KK(MD)+1
      YY(JJ) = XTRMAG(MD,I)
      XX(JJ) = FREQ(I)
      LM = MODE(MD,I)
35    CONTINUE
      GO TO 99
40    DO 45 I=1,NF
      IF(MODE(MD,I) .EQ. 0) GO TO 45
      JJ = I-KK(MD)+1
      YY(JJ) = XTRANG(MD,I)
      XX(JJ) = FREQ(I)
      LM = MODE(MD,I)
45    CONTINUE
      GO TO 99
50    DO 55 I=1,NF
      IF(MODE(MD,I) .EQ. 0) GO TO 55
      JJ = I-KK(MD)+1
      YY(JJ) = RETHP(MD,I)
      XX(JJ) = FREQ(I)
      LM = MODE(MD,I)
55    CONTINUE
      GO TO 99
60    DO 65 I=1,NF
      IF(MODE(MD,I) .EQ. 0) GO TO 65
      JJ = I-KK(MD)+1
      YY(JJ) = IMTHP(MD,I)
      XX(JJ) = FREQ(I)
      LM = MODE(MD,I)
65    CONTINUE
      GO TO 99
 70   DO 75 I=1,NF
      IF(MODE(MD,I) .EQ. 0) GO TO 75
      JJ = I-KK(MD)+1
      YY(JJ) = PHVOC(MD,I)
      XX(JJ) = FREQ(I)
      LM = MODE(MD,I)
 75   CONTINUE
      GO TO 99
 80   DO 85 I=1,NF
      IF(MODE(MD,I) .EQ. 0) GO TO 85
      JJ = I-KK(MD)+1
      YY(JJ) = ATT(MD,I)
```

```
      XX(JJ) = FREQ(I)
      LM = MODE(MD,I)
 85   CONTINUE
 99   RETURN
      END
```

```
      SUBROUTINE SPLINE (X, Y, B, C, D, N)
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION X(1), Y(1), B(1), C(1), D(1)
C
C   SPLINE DETERMINES THE COEFFICIENTS B, C, D,
C   OF A CUBIC SPLINE INTERPOLATING THE GIVEN
C   CURVE (X(I),Y(I)), I=1,...,N.  IF
C   X(I).LE.XX.LE.X(I+1) AND H = XX - X(I),
C   THEN THE INTERPOLATED VALUE AT XX IS
C   F(XX) = Y(I) + B(I)*H + C(I)*H**2 + D(I)*H**3.
C   THE INTERPOLATED VALUE CAN BE EVALUATED
C   WITH THE FUNCTION SP EVAL.
C   B,C,D, MUST HAVE LENGTH AT LEAST N.
C
      IF (N.GT.2)  GO TO 050
      C(1) = 0.0
      D(1) = 0.0
      B(1) = (Y(2) - Y(1)) / (X(2) - X(1))
      RETURN
  050 NN = N - 1
      TB = 0
      DO 100  I = 1,NN
      IF (X(I+1).LE.X(I))  GO TO 800
      D(I) = X(I+1) - X(I)
      TA = (Y(I+1) - Y(I)) / D(I)
      C(I) = TA - TB
      TB = TA
  100 CONTINUE
      C(1) = 0
      C(N) = 0
C
      TA = 0
      TB = 0
      DO 200  I = 2,NN
      C(I) = C(I) - TA * C(I-1)
      B(I) = 2.0 * (D(I) + D(I-1)) - TA * TB
      TB = D(I)
      TA = TB / B(I)
  200 CONTINUE
C
      C(NN) = C(NN) / B(NN)
      IF (NN.LT.3)  GO TO 350
      DO 300  I = 3,NN
      J = NN + 2 - I
  300 C(J) = (C(J) - D(J) * C(J+1)) / B(J)
  350 DO 400  I = 1,NN
      B(I) = (Y(I+1) - Y(I)) / D(I)
     $ - (C(I) + C(I) + C(I+1)) * D(I)
      D(I) = (C(I+1) - C(I)) / D(I)
      C(I) = 3.0 * C(I)
  400 CONTINUE
      RETURN
  800 PRINT 900
      PRINT 901, I,X(I),X(I+1)
```

```
      RETURN
901 FORMAT (1X,'   I =',I5,'  X(I) =',1PE12.5,'  X(I+1) =',1PE12.5 /)
900 FORMAT (' ERROR IN SPLINE',/,
   $ ' X-COORDINATE VALUES ARE NOT IN INCREASING ORDER')
    END
```

```
      SUBROUTINE TRXMTR(F)
      IMPLICIT REAL*8(A-H,O-Z)
       COMPLEX*16 IM/(0.0D0,1.0D0)/
      COMPLEX*16 XMTR
      COMMON/ONE/XMTR
      COMMON/FOUR/A(4),GAM(4),TAUP,TAUV,VO
      DATA PI/3.14159265358979324D0/
      TWOPI = PI*2.0D0
      XMTR=(0.0D0,0.0D0)
      OMEGA=TWOPI*F
      DO 30 I=1,4
30    XMTR=XMTR+A(I)/((GAM(I)+IM*OMEGA)**2)*(1.D0-CDEXP
     $  (-TAUP*(IM*OMEGA+GAM(I))))/(1.0D0+TAUV*(IM*OMEGA+GAM(I))))
      XMTR=XMTR*VO
      RETURN
      END
```

```
      SUBROUTINE RECVR(F)
      IMPLICIT REAL*8(A-H,O-Z)
       COMPLEX*16 IM/(0.0D0,1.0D0)/
      COMPLEX*16 RCVR
       INTEGER P,Q
      COMMON/TWO/RCVR
      COMMON/FIVE/GA,OMEGA1,OMEGA2,P,Q
      DATA PI/3.141592653589793240D0/
      TWOPI = PI*2.0D0
      OMEGA=TWOPI*F
      RCVR=GA*(IM*OMEGA/OMEGA1)**P/((1.D0+IM*OMEGA/
     $OMEGA1)**P*(1.D0+IM*OMEGA/OMEGA2)**Q)
      RETURN
      END
```

```
      SUBROUTINE CHANEL(F)
      IMPLICIT REAL*8(A-H,O-Z)
      COMPLEX*16 CONST
       COMPLEX*16 IM/(0.0D0,1.0D0)/
       COMPLEX*16 MSUM,CPXSIN,EXC,CHNL
      REAL*8 IMTHP
      COMMON/THREE/CHNL
      COMMON/SIX/MODE(15,50)
      COMMON/SEVEN/FREQ(50),XTRMAG(15,50),XTRANG(15,50),RETHP(15,50),
     $  IMTHP(15,50),ATT(15,50),PHVOC(15,50),NFVF,NF,NM
      COMMON/NINE/RHO
      COMMON/TEN/YC(6,15,50),BC(6,15,50),CC(6,15,50),DC(6,15,50)
      COMMON/ELEVEN/KK(15)
      DIMENSION         XX(50),YY(50),B(50),C(50),D(50),E(6)
      DATA VLITE/2.997925D5/
      DATA PI/3.14159265358979324D0/
       DATA ERAD/6.371D3/
      TWOPI = PI*2.0D0
      CONST=9.02D-14*(IM*F)**1.5
      SNRHO=DSIN(RHO/ERAD)
      SNRHO=DSQRT(SNRHO)
      MSUM = (0.0D0,0.0D0)
      DO 45 MD=1,NM
      LF=0
23    INIT=0
      LF=LF+1
      DO 25 I=1,NF
      IF(MODE(MD,I) .EQ. 0) GO TO 25
      JJ = I-KK(MD)+1
      MF = MODE(MD,I)
      XX(JJ) = FREQ(I)
      YY(JJ) = YC(LF,MD,JJ)
      B(JJ) = BC(LF,MD,JJ)
      C(JJ) = CC(LF,MD,JJ)
      D(JJ) = DC(LF,MD,JJ)
25    CONTINUE
      IF (F.GE.XX(1)) GO TO 30
      GO TO 45
30    IF(F.LE.XX(MF))GO TO 33
      GO TO 45
33    CONTINUE
      E(LF)=SPEVAL(F,XX,YY,B,C,D,MF,INIT)
35    IF(LF.LT.4) GO TO 23
      CPXSIN=CDSIN(E(3)+IM*E(4))
      EXC=E(1)*(DCOS(E(2))+IM*DSIN(E(2)))
      CAY=TWOPI*F/VLITE
      MSUM=MSUM+EXC*CDEXP(-IM*CAY*RHO*(CPXSIN-1.D0))
45    CONTINUE
      CHNL=CONST*MSUM/SNRHO
      RETURN
      END
```

```
      FUNCTION  SPEVAL (XVAL, X, Y, B, C, D, N, INIT)
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION X(1), Y(1), B(1), C(1), D(1)
C
C   SP EVAL EVALUATES THE INTERPOLATING CUBIC SPLINE
C   FOR THE DATA (X(I),Y(I)), I=1,...N AT X = XVAL.
C   IT IS ASSUMED THAT THE CUBIC POLYNOMIALS GIVEN
C   IN B(I), C(I), D(I) HAVE BEEN PREVIOUSLY
C   COMPUTED BY THE SUBROUTINE SPLINE OR PSPLIN.
C   INIT IS AN ESTIMATE OF THE INTERVAL WHERE XVAL
C   LIES, X(INIT).LE.XVAL.LE.X(INIT+1), BUT NEED
C   NOT BE USED.  SET INIT=0 IF THERE IS NO ESTIMATE.
C   ON RETURN, INIT WILL CONTAIN THE INTERVAL NUMBER.
C
      FN = N - 1
      EPS = 1.0E-3 * (X(N) - X(1)) / FN
      IF (XVAL.LT.X(1)-EPS)  GO TO 800
      IF (XVAL.GT.X(N)+EPS)  GO TO 800
      IF (INIT.LE.0)  GO TO 200
      IF (INIT.GE.N)  GO TO 200
C
      IF (XVAL.LT.X(INIT))  GO TO 150
  100 IF (XVAL.LT.X(INIT+1))  GO TO 300
         IF (INIT+1.GE.N)  GO TO 300
      INIT = INIT + 1
      GO TO 100
  150 INIT = INIT - 1
      IF (INIT.LE.0)  GO TO 200
      IF (XVAL.GE.X(INIT))  GO TO 300
      GO TO 150
C
  200 INIT = 1
      GO TO 100
C
  300 H = XVAL - X(INIT)
       SPEVAL = Y(INIT) +
     $ ((D(INIT)*H + C(INIT))*H + B(INIT))*H
      RETURN
  800 PRINT 900
      PRINT 901,  XVAL,X(1),X(N)
            RETURN
  900 FORMAT (' ERROR IN SP EVAL',/,
     $ ' XVAL OUT OF INTERPOLATION RANGE')
  901 FORMAT (5X,' XVAL =',1PE12.5,'  X(1) =',1PE12.5,' X(N)=',1PE12.5/)
      END
```

```
      SUBROUTINE NLOGN (N,X,Y,SIGNT,A,B)
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION X(1), Y(1), M(15)
      LX = 2**N
      FLX = LX
      FLXI1=(B-A)/FLX
      PI2=6.283185307
      PI24 = (-PI2/4.0 )
      DO 1 I = 1,N
    1 M(I) = 2**(N-I)
      DO 4 L = 1,N
      NBLOCK = 2**(L-1)
      LBLOCK = LX/NBLOCK
      LBHALF = LBLOCK/2
      KO = 0
      DO 4 IBLOCK = 1, NBLOCK
      ISTART = LBLOCK*(IBLOCK - 1)
      FK = KO
      V = (SIGNT*PI2*FK)/FLX
      Z1=DCOS(V)
      Z2=DSIN(V)
      IF (DABS(V - PI24) - 1.0D-6) 11, 12, 12
   11 Z2 = -1.0
   12 CONTINUE
      DO 2 I = 1, LBHALF
      J = ISTART + I
      K = J + LBHALF
      Q1 = X(K)*Z1 - Y(K)*Z2
      Q2 =  Y(K)*Z1 + X(K)*Z2
      X(K) = X(J) - Q1
      Y(K) = Y(J) - Q2
      X(J) = X(J) + Q1
      Y(J) = Y(J) + Q2
    2  CONTINUE
      DO 3 I = 2, N
      II = I
      LL =     AND(M(I),KO)
      IF(LL) 4,4,3
    3  KO = KO - M(I)
    4  KO = KO + M(II)
      KO = 0
      DO 50 K = 1, LX
      K1 =KO + 1
      IF (K1-K)55,55,65
   65  H1 = X(K1)
      H2 = Y(K1)
      X(K1) = X(K)
      Y(K1) = Y(K)
      X(K)=H1
      Y(K)=H2
   55  CONTINUE
      DO 85 I = 1, N
      II = I
      LL =     AND(M(I),KO)
```

```
      IF (LL) 75,75,85
   85  KO = KO - M(I)
   75  KO = KO + M(II)
   50  CONTINUE
      DO 100 K=1,LX
      OM=PI2*(K-1)/(B-A)
      IF(K .NE. 1) GO TO 9
      G=FLXI1
      GO TO 10
    9  G=(4.*(DSIN(OM*FLXI1/2.))**2)/(OM*OM)
       G=G/FLXI1
   10  CONTINUE
      X(K)=X(K)*G
      Y(K)=Y(K)*G
  100 CONTINUE
      RETURN
      END
```

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