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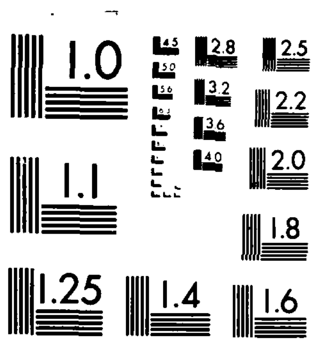


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NOSC TR 851

## Technical Report 851

# A PROGRAM TO COMPUTE VERTICAL ELECTRIC ELF FIELDS IN A LATERALLY INHOMOGENEOUS EARTH-IONOSPHERE WAVEGUIDE

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and
RA Pappert
Environmental Sciences Department

1 December 1982

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Approved for public release; distribution unlimited



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A computer program for calculating ELF propagation in a laterally nonuniform earth ionosphere waveguide is presented. The program is based on a simple surface propagation model formulated in terms of an integral equation which is solved using a moment method. The disturbance must be localized to the extent that the waveguide disturbance must effectively vanish outside a rectangle of several megameters on a side. The program allows for modeling rectangular, circular, and elliptical disturbances. The lateral propagation function for the vertical electric dipole is calculated. Waveguide height effects are allowed for within the spirit of the WKB approximation. The total vertical electric field is also calculated.


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# I. INTRODUCTION

Since an ELF signal from a remote transmitter is received over a range of azimuth angles, lateral ionospheric gradients produced by sporadic E layering or nuclear depressions can produce significant effects on propagation in the lower ELF band. This is because the Fresnel zone size can be large as compared with the distance over which the ionosphere changes significantly in the lateral direction. Although a number of workers have addressed the question of off-path effects (Wait[1], Galejs[2], Greifinger and Greifinger[3], Field [4,5], Field and Joiner [6,7], Pappert [8]) no formulation exists which can fully account for the propagation effects produced by a localized disturbance with simultaneous allowance for vertical inhomogeneity, lateral inhomogeneity, and anisotropy in a spherical geometry. It has been common practice to estimate the effects of lateral gradients by using a simple surface propagation model introduced by Wait and more fully developed by the Greifingers and Field. The formulation reduces the problem to an integral equation description of propagation along the earth's surface. The theory is predicated on the palatable assumption that the field can be separated into lateral and height dependent functions when the lateral ionspheric gradients are considerably smaller than the vertical gradients. When applying the method to nocturnal environments additional assumptions are made. Among these is the omission of nonreciprocal effects. This is well justified in the ambient case[9] as well as for daytime and depressed ionospheres. However, it is known that under sporadic E layering considerable mixing between TE and TM wave can occur[10]. Thus, when the surface propagation model is applied to sporadic E environments the scattered TE component is neglected. The validity conditions for the formulation are probably best satisfied under conditions of either natural or man-made depressed ionospheres.

The purpose of this report is to document a computer program, based on the surface propagation model, which is useful to the user community for estimating the effects of localized ionospheric disturbances on propagation of the vertical electric field component $E_z$ at lower ELF frequencies. A moments method[11] serves as the basis for the solution of the integral equation. Though the method is powerful, in the present program, practical storage requirements restrict application to disturbances which effectively vanish outside a rectangle of several megameters on one side. It is hoped that limitation will be relaxed in future work. The program allows in some measure, for modeling of rectangular, circular, and elliptical disturbance shapes. The lateral propagation function, W, defined as the ratio of the disturbed laterally dependent part of the vertical field component, $E_z$, to the undisturbed field component is calculated as is the absolute value of the total $E_z$ field component in the disturbed guide. The latter calculation allows in approximate manner for guide height effects via WKB formalism as applied to waveguide propagation.

The program requires eigenangle inputs for both the ambient and disturbed regions of the guide as well as end-on horizontal dipole excitation factors for the vertical $E_z$ field component. These must be supplied from a waveguide program such as that of reference 12.

## II. SUMMARY OF EQUATIONS

Subject to the assumption that the vertical, $E_z$, field component can be separated into lateral and height dependent functions, the lateral dependence $\psi(x,y)$ is given by[5]

$$\psi(x,y) = \psi^i(x,y) - \frac{ik^2}{4} \int_{-\infty}^{\infty}\int dx'dy' \left(S^2(x',y') - S_0^2\right) G\left(|\vec{r}-\vec{r}'|\right) \psi(x',y') \tag{1}$$

where S is the sine of the eigenangle for the disturbed guide, $S_0$ the sine for the unperturbed guide, k the free space wave number, and the superscript i signifies the unperturbed incident field. The Green's function $G(|\vec{r}-\vec{r}'|)$ is given by

$$G(|\vec{r}-\vec{r}'|) = \sqrt{\frac{|\vec{r}-\vec{r}'|}{a_e \sin\left(\frac{|\vec{r}-\vec{r}'|}{a_e}\right)}} \; H_0^{(2)}\left\{kS_0|\vec{r}-\vec{r}'|\right\} \tag{2}$$

where

$$\vec{r} = x\vec{i} + y\vec{j} \quad \text{and} \quad \vec{r}' = x'\vec{i} + y'\vec{j}. \tag{3}$$

Here $a_e$ is the earth's radius and the x, y, z are the Cartesian coordinates. z is measured vertically upwards into the ionosphere and x is measured horizontally with x-z the *plane of incidence*. Unit vectors in the x and y directions are denoted by $\vec{i}$ and $\vec{j}$. The square root factor in equation (2) has been introduced to allow for the geometric spreading appropriate to a spherical geometry. Beyond that, x, y and x', y' are taken to be rectangular coordinates in a flat earth geometry. The quantity $H_p^{(2)}$ is the Hankel coordinates in a flat earth geometry. The quantity $H_p^{(2)}$ is the Hankel function of order p of the second kind. The unperturbed lateral dependent function, $\Psi^i$ , is taken to be appropriate for the vertical electric field, $E_z$, launched by the end-on component of a ground based horizontal electric dipole source oriented in the x direction and given by

$$\psi^i = B \sqrt{\frac{|\vec{r}|}{a_e \sin\left(\frac{|\vec{r}|}{a_e}\right)}} \; H_1^{(2)}\left\{kS_0 |\vec{r}|\right\} \frac{x}{|\vec{r}|} \tag{4}$$

where B is a constant. Again the square root factor allows for the spreading appropriate to a spherical geometry. The discrete analog of equation (1) for field points within the disturbed region consists of the N x N system of linear equations:

$$\sum_{n=1}^{N} A_{mn} \psi_n = \psi_m^i \quad ; \; m = 1,2,...,N \tag{5}$$

Allowance is made for modeling rectangular, circular, and elliptical disturbances by subdividing them into square mesh cells. It is common practice in such circumstances to simplify the integrations involving cylindrical functions by approximating each square cell by a circle of equal area. It is also common practice to take the electric field to be constant over the area of a cell. However, larger cells can be tolerated if the electric field is allowed to vary over the area of a cell. At least two methods of allowing for this variation have been described in the literature[13]. In this work the method called 'plane wave correction' is used. The method assumes isotropic propagation within and between each cell and that should be a reasonable approximation in the present problem since anisotropy of propagation at ELF frequencies is quite small. Translated into the notation of this work, the results of reference 13 yield for the A-matrix elements:

$$A_{mm} \simeq 1 + \left(\frac{S_m^2}{S_0^2} - 1\right)\left[\left(\frac{S_m^2}{S_0^2} + 1\right) + \frac{i\pi}{2} kS_0a \left(1 - \frac{1}{4}(kS_ma)^2\right) H_1^{(2)}(kS_0a) + \frac{i\pi}{4}(kS_ma)^2 H_2^{(2)}(kS_0a)\right] \tag{6}$$

$$A_{mn} = \frac{i\pi kS_0a}{2}\left(\frac{S_n^2}{S_0^2} - 1\right) G(|\vec{r}_m - \vec{r}_n|)\left[\left(1 - \frac{1}{4}(kS_na)^2\right) J_1(kS_0a) + \frac{1}{2}\left(\frac{S_n^2}{S_0^2}\right) kS_0a\ J_2(kS_0a)\right] \quad ; m \neq n \tag{7}$$

The Green's function, G, is given by equation (2) with $\vec{r}_m$ replacing $\vec{r}$ and $\vec{r}_n$ replacing $\vec{r}'$. Also, $J_p$ is the Bessel function of order p of the first kind. In terms of the $\Psi_n$ determined by equation (5), and the $A_{mn}$ given by equation (7), the field at a point, $\vec{r}_m$, exterior to the disturbed region is given by:

$$\psi(\vec{r}_m) = \psi^i(\vec{r}_m) - \sum_{n=1}^{N} A_{mn}\Psi_n \tag{8}$$

Equations (5) through (8) are used in the present program to determine the dB value,

$$W = 20 \log_{10}\{\psi(x,y)/\psi^i(x,y)\}, \tag{9}$$

of the disturbed lateral function relative to its undisturbed value.

Another output of the program makes allowance for dependence of the vertical electric field on height of the guide via the approximate WKB formalism. For a laterally homogeneous guide the $E_z$ field generated by the end-on component of a horizontal dipole may be expressed as

$$E_z \sim -iQ \frac{S^{3/2}}{\frac{\partial F}{\partial \theta}} \frac{\left(1-{}_{\perp}R_{\perp\perp}\bar{R}_{\perp}\right)}{{}_{\parallel}\bar{R}_{\parallel}} \left(1+{}_{\parallel}\bar{R}_{\parallel}\right) \left\{C\left(1-{}_{\parallel}\bar{R}_{\parallel}\right)\right\} \Psi(x,y) \tag{10}$$

where F is the modal function and $\partial F/\partial\theta$ its derivative evaluated at the eigenangle. S and C are the sine and cosine of the eigenangle. ${}_{\perp}\bar{R}_{\perp}$ and ${}_{\parallel}\bar{R}_{\parallel}$ are TE and TM Fresnel reflection coefficients referenced to the ground and ${}_{\perp}R_{\perp}$ is the ionospheric TE reflection coefficient referenced to the ground. In the absence of anisotropy the quantity $(1-{}_{\perp}R_{\perp\perp}\bar{R}_{\perp})$ would cancel an identical term occurring in the $(\partial F/\partial\theta)$ . The Fresnel coefficient ${}_{\parallel}\bar{R}_{\parallel}$ is

$${}_{\parallel}\bar{R}_{\parallel} = \left(N_G^2\, C - \sqrt{N_G^2 - S^2}\ \right)/\left(N_G^2\, C + \sqrt{N_G^2 - S^2}\ \right) \tag{11}$$

where $N_G$ is the complex refractive index of the ground. Because the magnitude of $N_G$ is much greater than unity in the lower ELF band good approximations are:

$$1 + {}_{\parallel}\bar{R}_{\parallel} \simeq 2 \quad \text{and} \quad C\left(1-{}_{\parallel}\bar{R}_{\parallel}\right) \simeq 2/N_G \tag{12}$$

Thus, within the spirit of the WKB approximation the $E_z$ field becomes

$$E_z \approx -4Qi\left[\frac{S^{3/2}}{\frac{\partial F}{\partial \theta}}\left(1 - {}_{\perp}R_{\perp\perp}\bar{R}_{\perp}\right)\right]_r^{1/2}\left[\frac{S^{3/2}}{\frac{\partial F}{\partial \theta}}\left(1 - {}_{\perp}R_{\perp\perp}\bar{R}_{\perp}\right)\right]_t^{1/2}\frac{1}{N_{G\,t}}\Psi(x,y) \qquad (13)$$

where Q is a constant dependent upon dipole moment and frequency and the subscripts r and t stand for receiver and transmitter. That is, the first term in parenthesis is evaluated at the receiver while the second term in parenthesis and the factor $N_G^{-1}$ are evaluated at the transmitter.

The factor B in equation (4) is taken to be

$$B = \sqrt{\frac{\pi k S_0 a_e}{2}}\; e^{-(3/4)\pi i} \qquad (14)$$

To express the vertical electric field, $E_z$, as given by equation (13) in microvolts/m, the factor Q has the value

$$Q = 2.849 \times 10^{-3}\, f_{kHz}^{3/2}\,(Idl) \qquad (15)$$

where $f_{kHz}$ is the frequency in kHz and Idl is the current moment in ampere meters.

## III. GEOMETRICAL MODELING OF THE DISTURBANCE

As described in the introduction, the program can be used to model square, rectangular, circular, and elliptical disturbances. In all cases the disturbance is defined to be symmetrical about both its x and y axes. The special case of a rectangular disturbance is required to be uniformly disturbed. Let $x_0$ and $y_0$ denote the coordinates of the center of the disturbance with respect to the location of the transmitter. Let $L_x$ and $L_y$ be the size of the disturbance along the x and y axis. The disturbance is overlaid by a grid which has $n_x$ squares along the x axis and $n_y$ squares along the y axis. The choice of $L_x$, $L_y$, $n_x$, and $n_y$ must be such that $L_x/n_x = L_y/n_y$.

Since we assume that the disturbance is symmetrical about the x and y axis, we only need to specify the waveguide eigen solution parameters along the x axis. Let us denote these solutions by $S_i$. We take $i = 0$ to denote the ambient or undisturbed values. The remaining $S_i$ ($S_1$ through $S_N$) is assumed to be uniformly distributed along the x axis from $x_0$ to $x_0 + \frac{1}{2} L_x$. Note that the value of $n_x$ is not related to that of N. If $N = 1$, then a uniform disturbance will be assumed. This is required for the rectangular disturbance. The remaining problem is to fill the disturbance grid with interpolated values of S.

Let us now consider a single subsquare within a square disturbance. Let the coordinates of the center of this subsquare be x and y. The smaller value of $|x - x_0|$ and $|y - y_0|$ is used to interpolate a value of S from the input list of $S_i$. This results in the disturbance grid being filled as illustrated in figure 1. In the figure the similarly shaded regions would all have the same value of S.

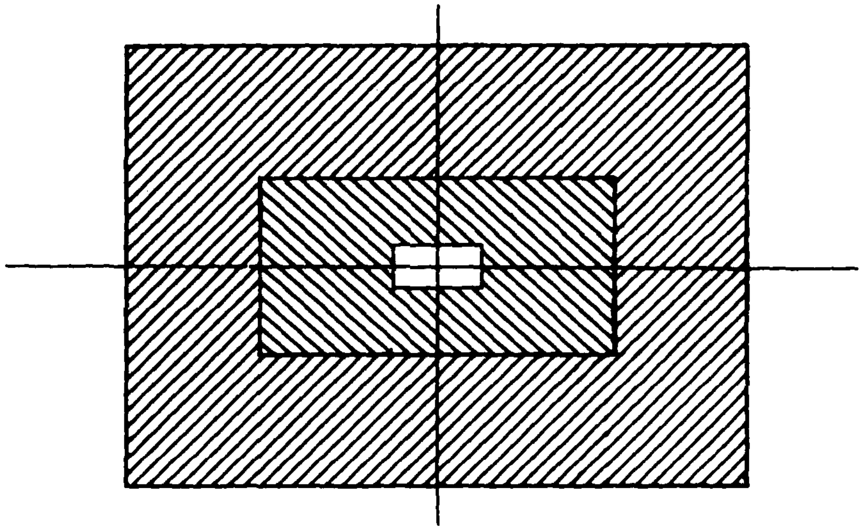

Figure 1. Diagram illustrating the distribution of S within a rectangular disturbance. The similarly shaded regions have the same value of S.

Let us consider an elliptical disturbance with an axial ratio $R = L_y/L_x$. The center of a given subsquare is at x and y. We can define an ellipse which is concentric with that of the outer edge of the disturbance. This ellipse intersects the x axis at a distance from $x_0$ defined by

$$A = \{(x-x_0)^2 + [(y-y_0)/R]^2\}^{1/2} \tag{16}$$

The above expression can be used to calculate the value of A for each corner of the subsquare, say $A_i$ where i = 1, 2, 3 or 4. If the smallest of the $A_i$ is greater than $L_x$, then the subsquare is entirely outside the disturbance and $S_0$ is used in the grid at that subsquare. If the largest of the $A_i$ is less than $L_x$, then the subsquare is entirely inside the disturbance and the value of S for that subsquare is interpolated from the input list of $S_i$. The remaining case is that of a subsquare on the edge of the disturbance. In this case the subsquare is subdivided into 16 smaller squares. Let the coordinates of the center of each of these smaller squares be $x_m$ and $y_m$. For each of these squares we calculate $A_m$ using equation (16). The value of S for the subsquare is given by

$$S = \frac{nS_N - (16-n)S_0}{16} \tag{17}$$

where n is the number of subsquares which are within the ellipse. A circular disturbance is treated the same way as an elliptical one with R = 1.

# IV. DESCRIPTION OF INPUT

All input to the sporadic-E program is given in a data deck on the standard input unit. A listing of sample input showing the data deck setup is shown in figure 2.

There are two parts to the input. This first part is read in by means of a FORTRAN NAMELIST input format. The first card of each set of input must contain '&DATUM' in columns 2-7. This is followed by at least one blank and then data items separated by commas. The data items have the following forms:

'variable name' = constant,

or

'array name' = set of constants (all separated by commas).

The data list is terminated by '&END'. All cards must have a blank in column 1.

The second part of the input follows the NAMELIST. The first card for this part is an identification card. It contains up to 80 columns of alpha-numeric information and is used to label the output plots. Following the identification card a series of punched cards (obtained from the programs described in reference 14 with NPUNCH = 1) is input for each mode.

The first card gives the values of R, FREQ, AZIM, CODIP, MAGFLD, SIGMA and EPSR. Next there are two cards per mode. The first of these contains the complex eigenangle at the ground and values for the complex quantities T1 and T2. The second card contains the eigenangle at the ground (duplicate input) and values for T3 and T4. The quantities T1, T2, T3, and T4 are defined in reference 14.

```
&DATUM
DM=6.75D6,
DMIN=150.,DMAX=15000.,DELD=150.,
YMAX=0.,DELY=0.,
IFLAG=2,IGRID=0.
XO=2000.,YO=0.,
NUMX=4,NUMY=8,
SIZEX= 500.,SIZEY=1000.,
IPLOT=1,
XLNG=5.,YLNG=8.,
EXTIC=3000.,WXTIC=3000.,WYTIC=1.,EYTIC=5.,
WMIN=-6.,WMAX=2.,
EMIN=5.,EMAX=45.,
&END
SAMPLE  X-VARIATION PLOT
R    .000 F 0.0750 A 105.000 C   13.000 M 0.4100-004 S 3.200-004 E 10.
1 83.98519-34.969091 7.15494419-002 2.04701227+000-3.39161358-002 1.5526
2 83.98519-34.969091

R    .000 F 0.0750 A 105.000 C   13.000 M 0.4100-004 S 3.200-004 E 10.
1 59.39295-65.552161-3.75059881-001 1.76435304+000 1.40913790+000 3.5235
2 59.39295-65.552161
```

Figure 2. Sample data input for the computer program.

The following variables and arrays may be specified in the NAMELIST input:

| | |
|---|---|
| DM | dipole moment in ampere meters. |
| DMIN | the minimum range in kilometers at which fields are calculated, printed, and plotted for IFLAG = 2. |
| DMAX | the maximum range in kilometers at which fields are calculated, printed, and plotted for IFLAG = 2. |
| DELD | the increment, in kilometers at which fields are calculated, printed, and plotted for IFLAG = 2. |
| YMAX | the maximum off axis value, in kilometers, at which fields are calculated, printed, and plotted for IFLAG = 1. |
| DELY | the increment in kilometers, at which fields are calculated printed and plotted for IFLAG = 1. |
| IFLAG | for IFLAG = 1 the program calculates fields as a function of y - the distance is fixed at DMIN and the disturbance moves in the y direction.<br>for IFLAG = 2 the program calculates fields as a function of distance with the disturbance fixed. |
| IGRID | IGRID = 0 indicates that the disturbance is either square or rectangular.<br>IGRID = 1 indicates that the disturbance is either circular or elliptical. |
| X0,Y0 | coordinates in kilometers at center of disturbance. Y0 is also the initial value at which fields are calculated, printed, and plotted for IFLAG = 1. |
| NUMX, NUMY | the disturbance is divided into NUMX grids in the x- direction and NUMY grids in the y-direction (these are $n_x$, $n_y$ in the text). |
| SIZEX SIZEY | defines the physical size of the disturbance. It is SIZEX kilometers by SIZEY kilometers. |
| IPLOT | a flag controlling whether or not plots are generated. If IPLOT = 0 no plots are generated. If IPLOT = 1 two plots are generated. For IFLAG=2 the first plot is WMAG(DB) vs X(KM), equation (9). The second plot consists of two curves: EZUMAG (DB), equations (13) and (4), is a solid curve and EZPMAG (DB), equations (13) and (8), is a dashed curve. For IFLAG=1 WMAG, EZUMAG, and EZPMAG are plotted with respect to y for a fixed value of x. |

| | |
|---|---|
| XLNG<br>YLNG | the length in inches for the x-axis and y-axis for the field plots. |
| WMIN<br>WMAX | the minimum and maximum values, in dB, desired on y-axis for the WMAG plot. |
| EMIN<br>EMAX | the minimum and maximum values in DB desired on y-axis for the EZREL plot. |
| XYIC<br>YTIC | the units per tic mark along the x-axis and y-axis for both plots. |

Initial values of the namelist variables are presented in table 1.

TABLE 1

Namelist variables and initial values.

| NAME | INITIAL VALUE | UNITS |
|---|---|---|
| DM | 6.75E6 | Ampere meters |
| DMIN | 25.0 | Kilometers |
| DMAX | 1000.0 | Kilometers |
| DELD | 25.0 | Kilometers |
| YMAX | 5000.0 | Kilometers |
| DELY | 25.0 | Kilometers |
| IFLAG | 2 | |
| IGRID | 0 | |
| X0 | 0.0 | Kilometers |
| Y0 | 0.0 | Kilometers |
| NUM | 0 | |
| NUMY | 0 | |
| SIZEX | 1000.0 | Kilometers |
| SIZEY | 1000.0 | Kilometers |
| IPLOT | 0 | |
| XLNG | 5.0 | Inches |
| YLNG | 6.0 | Inches |
| WMIN | -6.0 | Decibels |
| WMAX | 2.0 | Decibels |
| EMIN | -60 | Decibels |
| EMAX | 2.0 | Decibels |
| XTIC | 200.0 | Kilometers |
| YTIC | 0.2 | Decibels |

## V. DESCRIPTION OF OUTPUT

A listing of sample output is shown in figure 3. The resulting plots are found in figures 4 through 7. Figures 4 and 5 are the output from IFLAG = 2. Figures 6 and 7 are the output from IFLAG = 1. The first section of output is an echoing of the namelist input variables. This is followed by a schematic drawing of the disturbed region showing grid numbers and the coordinates of the center of the corner meshes. The next section shows additional input parameters: the identification label that will be on the plots, the frequency, conductivity, dielectric function, and the complex eigenangle and excitation factor for each region. YMID represents the y-value coordinate of the midpoint of the disturbance.

In the printout, the tables for WI, EZ0, and EZS, are the magnitudes of the quantities as given by equations 9, 10, and 13. These quantities are computed at the midpoints of each grid square.

The last table in the printout lists the following quantities at the given distance from the transmitter along the x-axis at y=0:

| | |
|---|---|
| EZREL,EZANG | magnitude(dB) and phase angle (radians) of equation 8 |
| WMAG,WANG | magnitude(dB) and phase angle (radians) of equation 9 |
| EZUMAG,EZUANG | magnitude(dB) and phase angle (radians) of equation 10 |
| EZPMAG,EZPANG | magnitude(dB) and phase angle (radians) of equation 13 |

```
 $DATUM
DM = .67500000+007,DMIN = .15000000+003,DMAX = .15000000+005,DELD = .15000000+003,YMAX = .00000000     ,DELY = .00000000     ,
IFLAG =            2,IGRID =            0,XO = .20000000+004,YO = .00000000     ,NUMX =            4,NUMY =            8,
SIZEX = .50000000+003,SIZEY = .10000000+004,IPLOT =            1,XLNG = .50000000+001,YLNG = .80000000+001,WMIN =-.60000000+001,
WMAX = .20000000+001,EMIN = .50000000+001,EMAX = .45000000+002,EXTIC = .30000000+004,EYTIC = .50000000+001,WXTIC = .30000000+004,
WYTIC = .10000000+001
$END

 ____ ____ ____ ____
?    ?    ?    ?    ?
?  1 ?  2 ?  3 ?  4 ?
?    ?    ?    ?    ?
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?  5 ?  6 ?  7 ?  8 ?
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?    ?    ?    ?    ?
?  9 ? 10 ? 11 ? 12 ?
?    ?    ?    ?    ?
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? 17 ? 18 ? 19 ? 20 ?
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?    ?    ?    ?    ?
? 29 ? 30 ? 31 ? 32 ?
?    ?    ?    ?    ?
?____?____?____?____?

COORDINATES AT CENTER OF MESH NUMBER   1 ARE:  X= 1812.50 Y=  437.50
COORDINATES AT CENTER OF MESH NUMBER   4 ARE:  X= 2187.50 Y=  437.50
COORDINATES AT CENTER OF MESH NUMBER  29 ARE:  X= 1812.50 Y= -437.50
COORDINATES AT CENTER OF MESH NUMBER  32 ARE:  X= 2187.50 Y= -437.50
```

Figure 3. Sample printed output generated by the first case called out in the sample data.

```
SAMPLE  X-VARIATION PLOT
FREQ =    .750-001 SIGMA =    .320-003 EPSR=  10.00
 GRID       THETA                        XTRA
  0  83.98519 -34.96909    -8.960726708-001  -9.687796474+000
  1  59.39295 -65.55216    -2.835879266+000  -1.158006728+001

YMID =          .00
```

EZO

| | | | |
|---|---|---|---|
| 1.51+000 | 1.45+000 | 1.39+000 | 1.34+000 |
| 1.55+000 | 1.48+000 | 1.42+000 | 1.36+000 |
| 1.57+000 | 1.50+000 | 1.44+000 | 1.38+000 |
| 1.59+000 | 1.51+000 | 1.45+000 | 1.38+000 |
| 1.59+000 | 1.51+000 | 1.45+000 | 1.38+000 |
| 1.57+000 | 1.50+000 | 1.44+000 | 1.38+000 |
| 1.55+000 | 1.48+000 | 1.42+000 | 1.36+000 |
| 1.51+000 | 1.45+000 | 1.39+000 | 1.34+000 |

EZS

| | | | |
|---|---|---|---|
| 1.13+000 | 1.03+000 | 9.84-001 | 9.64-001 |
| 1.11+000 | 1.02+000 | 9.83-001 | 9.73-001 |
| 1.10+000 | 1.01+000 | 9.80-001 | 9.78-001 |
| 1.09+000 | 1.00+000 | 9.78-001 | 9.80-001 |
| 1.09+000 | 1.00+000 | 9.78-001 | 9.80-001 |
| 1.10+000 | 1.01+000 | 9.80-001 | 9.78-001 |
| 1.11+000 | 1.02+000 | 9.83-001 | 9.73-001 |
| 1.13+000 | 1.03+000 | 9.84-001 | 9.64-001 |

WI

| | | | |
|---|---|---|---|
| -2.5496 | -2.9501 | -3.0140 | -2.8561 |
| -2.8676 | -3.2269 | -3.1821 | -2.9128 |
| -3.1044 | -3.4413 | -3.3171 | -2.9656 |
| -3.2293 | -3.5572 | -3.3921 | -2.9972 |
| -3.2293 | -3.5572 | -3.3921 | -2.9972 |
| -3.1044 | -3.4413 | -3.3171 | -2.9656 |
| -2.8676 | -3.2269 | -3.1821 | -2.9128 |
| -2.5496 | -2.9501 | -3.0140 | -2.8561 |

| YMID | DIST | WMAG | WANG | EZREL | EZANG | EZUMAG | EZUANG | EZPMAG | EZPANG |
|---|---|---|---|---|---|---|---|---|---|
| .0 | 150.0 | -1.18907-001 | 6.27277+000 | -1.18907-001 | 3.13118+000 | 4.32795+001 | 4.58633+000 | 4.31606+001 | 1.43432+000 |
| .0 | 300.0 | -1.33171-001 | 6.25389+000 | -1.33172-001 | 3.11230+000 | 3.80944+001 | 4.43830+000 | 3.79612+001 | 1.26741+000 |
| .0 | 450.0 | 1.36797-003 | 6.23544+000 | 1.36797-003 | 3.09385+000 | 3.53506+001 | 4.24297+000 | 3.53520+001 | 1.05364+000 |
| .0 | 600.0 | 2.62075-001 | 6.22922+000 | 2.62075-001 | 3.08763+000 | 3.35259+001 | 4.02069+000 | 3.37880+001 | 8.25135-001 |
| .0 | 750.0 | 5.64055-001 | 6.24351+000 | 5.64055-001 | 3.10192+000 | 3.21635+001 | 3.78213+000 | 3.27276+001 | 6.00859-001 |
| .0 | 900.0 | 7.95926-001 | 6.27982+000 | 7.95926-001 | 3.13823+000 | 3.10727+001 | 3.53314+000 | 3.18686+001 | 3.88183-001 |
| .0 | 1050.0 | 8.52173-001 | 5.02191-002 | 8.52173-001 | 3.19181+000 | 3.01581+001 | 3.27715+000 | 3.10103+001 | 1.85776-001 |
| .0 | 1200.0 | 6.44459-001 | 1.11490-001 | 6.44459-001 | 3.25308+000 | 2.93663+001 | 3.01626+000 | 3.00107+001 | 6.26935+000 |
| .0 | 1350.0 | 1.01138-001 | 1.65756-001 | 1.01138-001 | 3.30735+000 | 2.86645+001 | 2.75183+000 | 2.87656+001 | 6.05918+000 |
| .0 | 1500.0 | -8.21781-001 | 1.89704-001 | -8.21781-001 | 3.33130+000 | 2.80315+001 | 2.48476+000 | 2.72097+001 | 5.81606+000 |
| .0 | 1650.0 | -2.06253+000 | 1.44464-001 | -2.06253+000 | 3.28606+000 | 2.74528+001 | 2.21567+000 | 2.53903+001 | 5.50173+000 |
| .0 | 1800.0 | -3.15872+000 | -1.40568-002 | -2.27585+000 | 3.05357+000 | 2.69181+001 | 1.94501+000 | 2.46422+001 | 4.99858+000 |
| .0 | 1950.0 | -3.54067+000 | -1.98468-001 | -2.65779+000 | 2.86916+000 | 2.64196+001 | 1.67311+000 | 2.37618+001 | 4.54227+000 |
| .0 | 2100.0 | -3.27364+000 | -3.16967-001 | -2.39076+000 | 2.75066+000 | 2.59516+001 | 1.40020+000 | 2.35608+001 | 4.15086+000 |
| .0 | 2250.0 | -2.81518+000 | 5.93701+000 | -2.81518+000 | 2.79541+000 | 2.55097+001 | 1.12647+000 | 2.26945+001 | 3.92188+000 |
| .0 | 2400.0 | -2.49667+000 | 5.96869+000 | -2.49667+000 | 2.82710+000 | 2.50903+001 | 8.52059-001 | 2.25936+001 | 3.67916+000 |
| .0 | 2550.0 | -2.27920+000 | 5.99499+000 | -2.27920+000 | 2.85340+000 | 2.46906+001 | 5.77082-001 | 2.24114+001 | 3.43048+000 |
| .0 | 2700.0 | -2.12389+000 | 6.01585+000 | -2.12389+000 | 2.87426+000 | 2.43083+001 | 3.01627-001 | 2.21844+001 | 3.17589+000 |

Figure 3. Continued.

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| .0 | 2850.0 | -2.00808+000 | 6.03243+000 | -2.00808+000 | 2.89084+000 | 2.39415+001 | 2.57626-002 | 2.19334+001 | 2.91660+000 |
| .0 | 3000.0 | -1.91842+000 | 6.04578+000 | -1.91842+000 | 2.90419+000 | 2.35886+001 | 6.03273+000 | 2.16701+001 | 2.65373+000 |
| .0 | 3150.0 | -1.84684+000 | 6.05670+000 | -1.84684+000 | 2.91511+000 | 2.32482+001 | 5.75622+000 | 2.14013+001 | 2.38814+000 |
| .0 | 3300.0 | -1.78824+000 | 6.06580+000 | -1.78824+000 | 2.92420+000 | 2.29192+001 | 5.47944+000 | 2.11310+001 | 2.12045+000 |
| .0 | 3450.0 | -1.73929+000 | 6.07347+000 | -1.73929+000 | 2.93188+000 | 2.26006+001 | 5.20243+000 | 2.08613+001 | 1.85113+000 |
| .0 | 3600.0 | -1.69769+000 | 6.08005+000 | -1.69769+000 | 2.93845+000 | 2.22916+001 | 4.92522+000 | 2.05939+001 | 1.58048+000 |
| .0 | 3750.0 | -1.66183+000 | 6.08574+000 | -1.66183+000 | 2.94415+000 | 2.19915+001 | 4.64782+000 | 2.03297+001 | 1.30878+000 |
| .0 | 3900.0 | -1.63055+000 | 6.09072+000 | -1.63055+000 | 2.94913+000 | 2.16996+001 | 4.37027+000 | 2.00690+001 | 1.03621+000 |
| .0 | 4050.0 | -1.60298+000 | 6.09512+000 | -1.60298+000 | 2.95353+000 | 2.14152+001 | 4.09258+000 | 1.98122+001 | 7.62922-001 |
| .0 | 4200.0 | -1.57845+000 | 6.09904+000 | -1.57845+000 | 2.95744+000 | 2.11379+001 | 3.81475+000 | 1.95595+001 | 4.89010-001 |
| .0 | 4350.0 | -1.55646+000 | 6.10255+000 | -1.55646+000 | 2.96096+000 | 2.08674+001 | 3.53682+000 | 1.93109+001 | 2.14600-001 |
| .0 | 4500.0 | -1.53658+000 | 6.10573+000 | -1.53658+000 | 2.96413+000 | 2.06030+001 | 3.25877+000 | 1.90665+001 | 6.22291+000 |
| .0 | 4650.0 | -1.51855-000 | 6.10861+000 | -1.51855+000 | 2.96702+000 | 2.03446+001 | 2.98065+000 | 1.88260+001 | 5.94767+000 |
| .0 | 4800.0 | -1.50198+000 | 6.11125+000 | -1.50198+000 | 2.96965+000 | 2.00918+001 | 2.70242+000 | 1.85899+001 | 5.67207+000 |
| .0 | 4950.0 | -1.48683+000 | 6.11366+000 | -1.48683+000 | 2.97207+000 | 1.98442+001 | 2.42413+000 | 1.83574+001 | 5.39620+000 |
| .0 | 5100.0 | -1.47280+000 | 6.11590+000 | -1.47280+000 | 2.97430+000 | 1.96018+001 | 2.14577+000 | 1.81290+001 | 5.12007+000 |
| .0 | 5250.0 | -1.45986+000 | 6.11796+000 | -1.45986+000 | 2.97637+000 | 1.93638+001 | 1.86736+000 | 1.79040+001 | 4.84372+000 |
| .0 | 5400.0 | -1.44771+000 | 6.11988+000 | -1.44771+000 | 2.97829+000 | 1.91308+001 | 1.58886+000 | 1.76831+001 | 4.56714+000 |
| .0 | 5550.0 | -1.43633+000 | 6.12165+000 | -1.43633+000 | 2.98006+000 | 1.89018+001 | 1.31026+000 | 1.74654+001 | 4.29032+000 |
| .0 | 5700.0 | -1.42603+000 | 6.12333+000 | -1.42603+000 | 2.98173+000 | 1.86762+001 | 1.03177+000 | 1.72502+001 | 4.01350+000 |
| .0 | 5850.0 | -1.41606+000 | 6.12490+000 | -1.41606+000 | 2.98330+000 | 1.84554+001 | 7.53127-001 | 1.70394+001 | 3.73643+000 |
| .0 | 6000.0 | -1.40607+000 | 6.12638+000 | -1.40607+000 | 2.98479+000 | 1.82404+001 | 4.74266-001 | 1.68343+001 | 3.45906+000 |
| .0 | 6150.0 | -1.39690+000 | 6.12774+000 | -1.39690+000 | 2.98615+000 | 1.80269+001 | 1.95346-001 | 1.66300+001 | 3.18149+000 |
| .0 | 6300.0 | -1.38865+000 | 6.12902+000 | -1.38865+000 | 2.98743+000 | 1.78157+001 | 6.19974+000 | 1.64271+001 | 2.90398+000 |
| .0 | 6450.0 | -1.38083+000 | 6.13030+000 | -1.38083+000 | 2.98871+000 | 1.76099+001 | 5.92111+000 | 1.62290+001 | 2.62664+000 |
| .0 | 6600.0 | -1.37028+000 | 6.13152+000 | -1.37028+000 | 2.98992+000 | 1.74157+001 | 5.64130+000 | 1.60455+001 | 2.34804+000 |
| .0 | 6750.0 | -1.36380+000 | 6.13256+000 | -1.36380+000 | 2.99097+000 | 1.72116+001 | 5.36250+000 | 1.58478+001 | 2.07028+000 |
| .0 | 6900.0 | -1.35635+000 | 6.13375+000 | -1.35635+000 | 2.99215+000 | 1.70193+001 | 5.08374+000 | 1.56629+001 | 1.79271+000 |
| .0 | 7050.0 | -1.35141+000 | 6.13486+000 | -1.35141+000 | 2.99327+000 | 1.68231+001 | 4.80571+000 | 1.54717+001 | 1.51580+000 |
| .0 | 7200.0 | -1.34480+000 | 6.13586+000 | -1.34480+000 | 2.99427+000 | 1.66335+001 | 4.52677+000 | 1.52887+001 | 1.23786+000 |
| .0 | 7350.0 | -1.33843+000 | 6.13683+000 | -1.33843+000 | 2.99523+000 | 1.64468+001 | 4.24780+000 | 1.51084+001 | 9.59848-001 |
| .0 | 7500.0 | -1.33235+000 | 6.13775+000 | -1.33235+000 | 2.99616+000 | 1.62631+001 | 3.96881+000 | 1.49307+001 | 6.81783-001 |
| .0 | 7650.0 | -1.32640+000 | 6.13865+000 | -1.32640+000 | 2.99705+000 | 1.60822+001 | 3.68979+000 | 1.47558+001 | 4.03664-001 |
| .0 | 7800.0 | -1.32069+000 | 6.13952+000 | -1.32069+000 | 2.99793+000 | 1.59041+001 | 3.41076+000 | 1.45834+001 | 1.25504-001 |
| .0 | 7950.0 | -1.31509+000 | 6.14035+000 | -1.31509+000 | 2.99876+000 | 1.57288+001 | 3.13171+000 | 1.44137+001 | 6.13047+000 |
| .0 | 8100.0 | -1.30953+000 | 6.14117+000 | -1.30953+000 | 2.99958+000 | 1.55561+001 | 2.85264+000 | 1.42466+001 | 5.85222+000 |
| .0 | 8250.0 | -1.30415+000 | 6.14196+000 | -1.30415+000 | 3.00037+000 | 1.53861+001 | 2.57356+000 | 1.40820+001 | 5.57392+000 |
| .0 | 8400.0 | -1.29907+000 | 6.14276+000 | -1.29907+000 | 3.00116+000 | 1.52188+001 | 2.29446+000 | 1.39197+001 | 5.29562+000 |
| .0 | 8550.0 | -1.29408+000 | 6.14349+000 | -1.29408+000 | 3.00190+000 | 1.50540+001 | 2.01534+000 | 1.37599+001 | 5.01724+000 |
| .0 | 8700.0 | -1.28961+000 | 6.14420+000 | -1.28961+000 | 3.00260+000 | 1.48918+001 | 1.73621+000 | 1.36022+001 | 4.73881+000 |
| .0 | 8850.0 | -1.28456+000 | 6.14496+000 | -1.28456+000 | 3.00337+000 | 1.47321+001 | 1.45707+000 | 1.34475+001 | 4.46044+000 |
| .0 | 9000.0 | -1.28031+000 | 6.14560+000 | -1.28031+000 | 3.00400+000 | 1.45749+001 | 1.17791+000 | 1.32946+001 | 4.18192+000 |
| .0 | 9150.0 | -1.27487+000 | 6.14628+000 | -1.27487+000 | 3.00469+000 | 1.44202+001 | 8.98744-001 | 1.31453+001 | 3.90343+000 |
| .0 | 9300.0 | -1.26393+000 | 6.14692+000 | -1.26393+000 | 3.00532+000 | 1.42680+001 | 6.19564-001 | 1.29980+001 | 3.62489+000 |
| .0 | 9450.0 | -1.26536+000 | 6.14757+000 | -1.26536+000 | 3.00598+000 | 1.41182+001 | 3.40373-001 | 1.28528+001 | 3.34635+000 |
| .0 | 9600.0 | -1.26084+000 | 6.14821+000 | -1.26084+000 | 3.00661+000 | 1.39708+001 | 6.11717-002 | 1.27100+001 | 3.06779+000 |
| .0 | 9750.0 | -1.25637+000 | 6.14884+000 | -1.25637+000 | 3.00724+000 | 1.38259+001 | 6.06515+000 | 1.25696+001 | 2.78920+000 |
| .0 | 9900.0 | -1.25196+000 | 6.14946+000 | -1.25196+000 | 3.00786+000 | 1.36834+001 | 5.78592+000 | 1.24315+001 | 2.51060+000 |
| .0 | 10050.0 | -1.24758+000 | 6.15007+000 | -1.24758+000 | 3.00847+000 | 1.35434+001 | 5.50669+000 | 1.22958+001 | 2.23198+000 |
| .0 | 10200.0 | -1.24324+000 | 6.15067+000 | -1.24324+000 | 3.00908+000 | 1.34057+001 | 5.22746+000 | 1.21625+001 | 1.95335+000 |
| .0 | 10350.0 | -1.23893+000 | 6.15127+000 | -1.23893+000 | 3.00967+000 | 1.32705+001 | 4.94821+000 | 1.20316+001 | 1.67470+000 |
| .0 | 10500.0 | -1.23464+000 | 6.15186+000 | -1.23464+000 | 3.01026+000 | 1.31377+001 | 4.66895+000 | 1.19030+001 | 1.39603+000 |
| .0 | 10650.0 | -1.23038+000 | 6.15244+000 | -1.23038+000 | 3.01085+000 | 1.30073+001 | 4.38969+000 | 1.17769+001 | 1.11735+000 |
| .0 | 10800.0 | -1.22613+000 | 6.15302+000 | -1.22613+000 | 3.01143+000 | 1.28794+001 | 4.11042+000 | 1.16532+001 | 8.38661-001 |
| .0 | 10950.0 | -1.22189+000 | 6.15359+000 | -1.22189+000 | 3.01200+000 | 1.27539+001 | 3.83114+000 | 1.15320+001 | 5.59959-001 |
| .0 | 11100.0 | -1.21766+000 | 6.15417+000 | -1.21765+000 | 3.01257+000 | 1.26309+001 | 3.55186+000 | 1.14132+001 | 2.81246-001 |
| .0 | 11250.0 | -1.21342+000 | 6.15473+000 | -1.21342+000 | 3.01314+000 | 1.25103+001 | 3.27257+000 | 1.12969+001 | 2.52413-003 |

Figure 3. Continued.

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| .0 | 11400.0 | -1.20919+000 | 6.15530+000 | -1.20918+000 | 3.01371+000 | 1.23923+001 | 2.99327+000 | 1.11831+001 | 6.00698+000 |
| .0 | 11550.0 | -1.20494+000 | 6.15587+000 | -1.20494+000 | 3.01427+000 | 1.22768+001 | 2.71397+000 | 1.10719+001 | 5.72824+000 |
| .0 | 11700.0 | -1.20068+000 | 6.15643+000 | -1.20068+000 | 3.01484+000 | 1.21639+001 | 2.43466+000 | 1.09632+001 | 5.44950+000 |
| .0 | 11850.0 | -1.19641+000 | 6.15699+000 | -1.19641+000 | 3.01540+000 | 1.20536+001 | 2.15535+000 | 1.08572+001 | 5.17075+000 |
| .0 | 12000.0 | -1.19211+000 | 6.15756+000 | -1.19211+000 | 3.01596+000 | 1.19459+001 | 1.87603+000 | 1.07538+001 | 4.89199+000 |
| .0 | 12150.0 | -1.18778+000 | 6.15812+000 | -1.18778+000 | 3.01653+000 | 1.18408+001 | 1.59670+000 | 1.06531+001 | 4.61323+000 |
| .0 | 12300.0 | -1.18342+000 | 6.15869+000 | -1.18342+000 | 3.01709+000 | 1.17385+001 | 1.31737+000 | 1.05551+001 | 4.33447+000 |
| .0 | 12450.0 | -1.17903+000 | 6.15926+000 | -1.17903+000 | 3.01766+000 | 1.16389+001 | 1.03804+000 | 1.04599+001 | 4.05570+000 |
| .0 | 12600.0 | -1.17459+000 | 6.15983+000 | -1.17459+000 | 3.01823+000 | 1.15422+001 | 7.58698-001 | 1.03676+001 | 3.77693+000 |
| .0 | 12750.0 | -1.17011+000 | 6.16040+000 | -1.17011+000 | 3.01881+000 | 1.14482+001 | 4.79354-001 | 1.02781+001 | 3.49816+000 |
| .0 | 12900.0 | -1.16557+000 | 6.16098+000 | -1.16557+000 | 3.01939+000 | 1.13572+001 | 2.00006-001 | 1.01917+001 | 3.21939+000 |
| .0 | 13050.0 | -1.16097+000 | 6.16157+000 | -1.16097+000 | 3.01997+000 | 1.12692+001 | 6.20384+000 | 1.01083+001 | 2.94063+000 |
| .0 | 13200.0 | -1.15630+000 | 6.16216+000 | -1.15630+000 | 3.02056+000 | 1.11843+001 | 5.92448+000 | 1.00280+001 | 2.66186+000 |
| .0 | 13350.0 | -1.15157+000 | 6.16275+000 | -1.15157+000 | 3.02116+000 | 1.11025+001 | 5.64512+000 | 9.95089+000 | 2.38310+000 |
| .0 | 13500.0 | -1.14675+000 | 6.16336+000 | -1.14675+000 | 3.02176+000 | 1.10239+001 | 5.36576+000 | 9.87710+000 | 2.10434+000 |
| .0 | 13650.0 | -1.14185+000 | 6.16397+000 | -1.14185+000 | 3.02237+000 | 1.09486+001 | 5.08639+000 | 9.80671+000 | 1.82558+000 |
| .0 | 13800.0 | -1.13685+000 | 6.16459+000 | -1.13685+000 | 3.02300+000 | 1.08767+001 | 4.80702+000 | 9.73982+000 | 1.54683+000 |
| .0 | 13950.0 | -1.13176+000 | 6.16522+000 | -1.13176+000 | 3.02363+000 | 1.08083+001 | 4.52765+000 | 9.67655+000 | 1.26809+000 |
| .0 | 14100.0 | -1.12655+000 | 6.16586+000 | -1.12655+000 | 3.02427+000 | 1.07436+001 | 4.24827+000 | 9.61703+000 | 9.89353-001 |
| .0 | 14250.0 | -1.12122+000 | 6.16651+000 | -1.12122+000 | 3.02492+000 | 1.06826+001 | 3.96889+000 | 9.56138+000 | 7.10626-001 |
| .0 | 14400.0 | -1.11576+000 | 6.16718+000 | -1.11576+000 | 3.02559+000 | 1.06255+001 | 3.68951+000 | 9.50976+000 | 4.31909-001 |
| .0 | 14550.0 | -1.11016+000 | 6.16786+000 | -1.11016+000 | 3.02627+000 | 1.05725+001 | 3.41012+000 | 9.46232+000 | 1.53204-001 |
| .0 | 14700.0 | -1.10441+000 | 6.16856+000 | -1.10441+000 | 3.02697+000 | 1.05237+001 | 3.13073+000 | 9.41925+000 | 6.15770+000 |
| .0 | 14850.0 | -1.09850+000 | 6.16928+000 | -1.09850+000 | 3.02768+000 | 1.04792+001 | 2.85134+000 | 9.38074+000 | 5.87902+000 |
| .0 | 15000.0 | -1.09240+000 | 6.17001+000 | -1.09240+000 | 3.02842+000 | 1.04394+001 | 2.57194+000 | 9.34699+000 | 5.60036+000 |

```
                    PLOTTING COMMENCING
                    ...................

 ..... DISSPLA VERSION 9.0 .....
 NO. OF FIRST PLOT  1



 PLOT NO.   1 WITH THE TITLE

 HAS BEEN COMPLETED.

 PLOT ID. READS
 PLOT 1     11.03.23  THUR 23 SEP, 1982
   JOB=SPORAD  ,              DISSPLA 9.0

 DATA FOR PLOT

 NO. OF CURVES DRAWN  1
 -----------------------------
 HORIZ. AXIS LENGTH   5.0 INS.
 VERT. AXIS LENGTH    8.0 INS.
```

Figure 3. Continued.

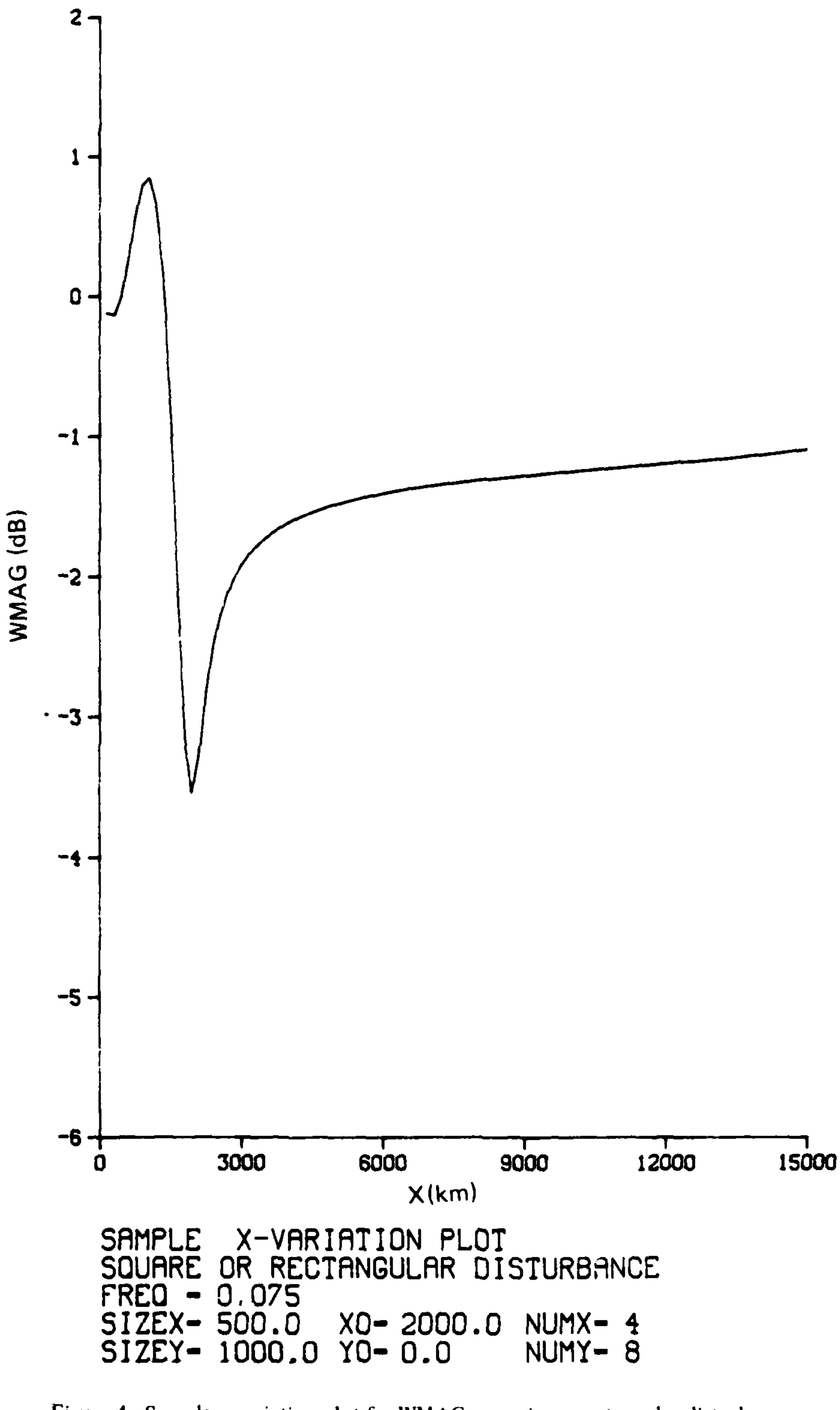


Figure 4. Sample x-variation plot for WMAG assuming a rectangular disturbance.

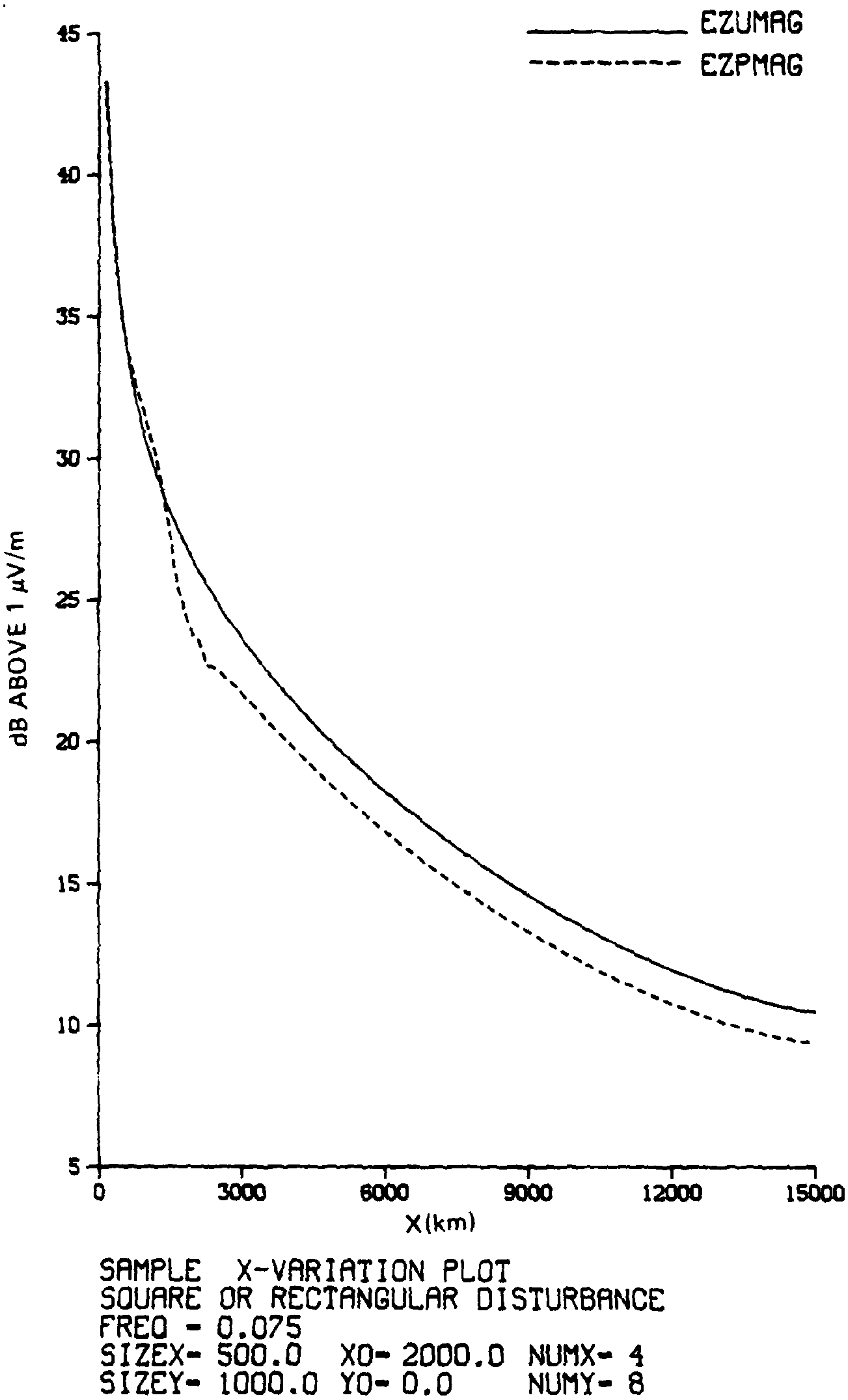


Figure 5. Sample x-variation plot for EZUMAG and EZPMAG assuming a rectangular disturbance.

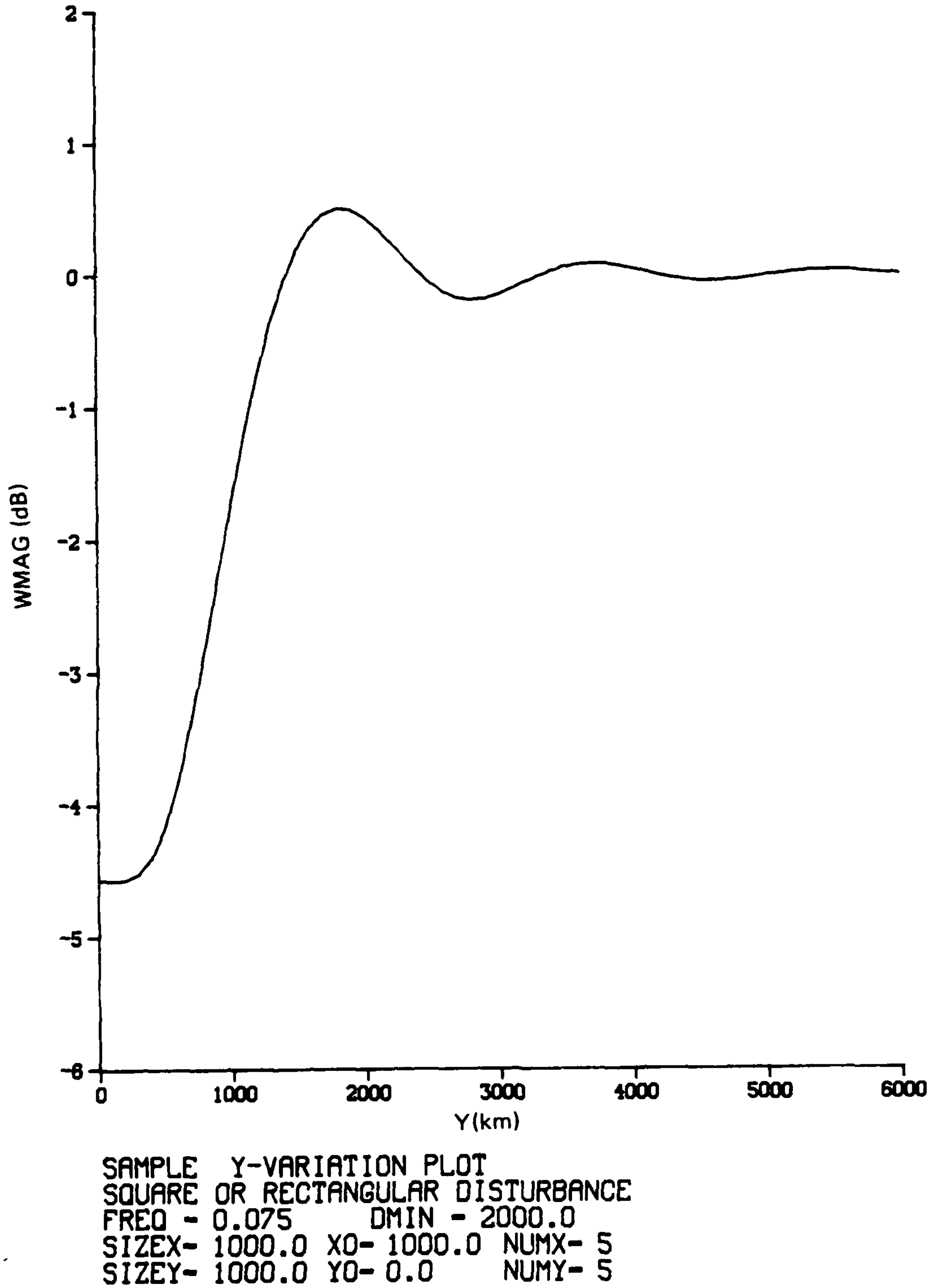


Figure 6. Sample y-variation plot for WMAG assuming a rectangular disturbance.

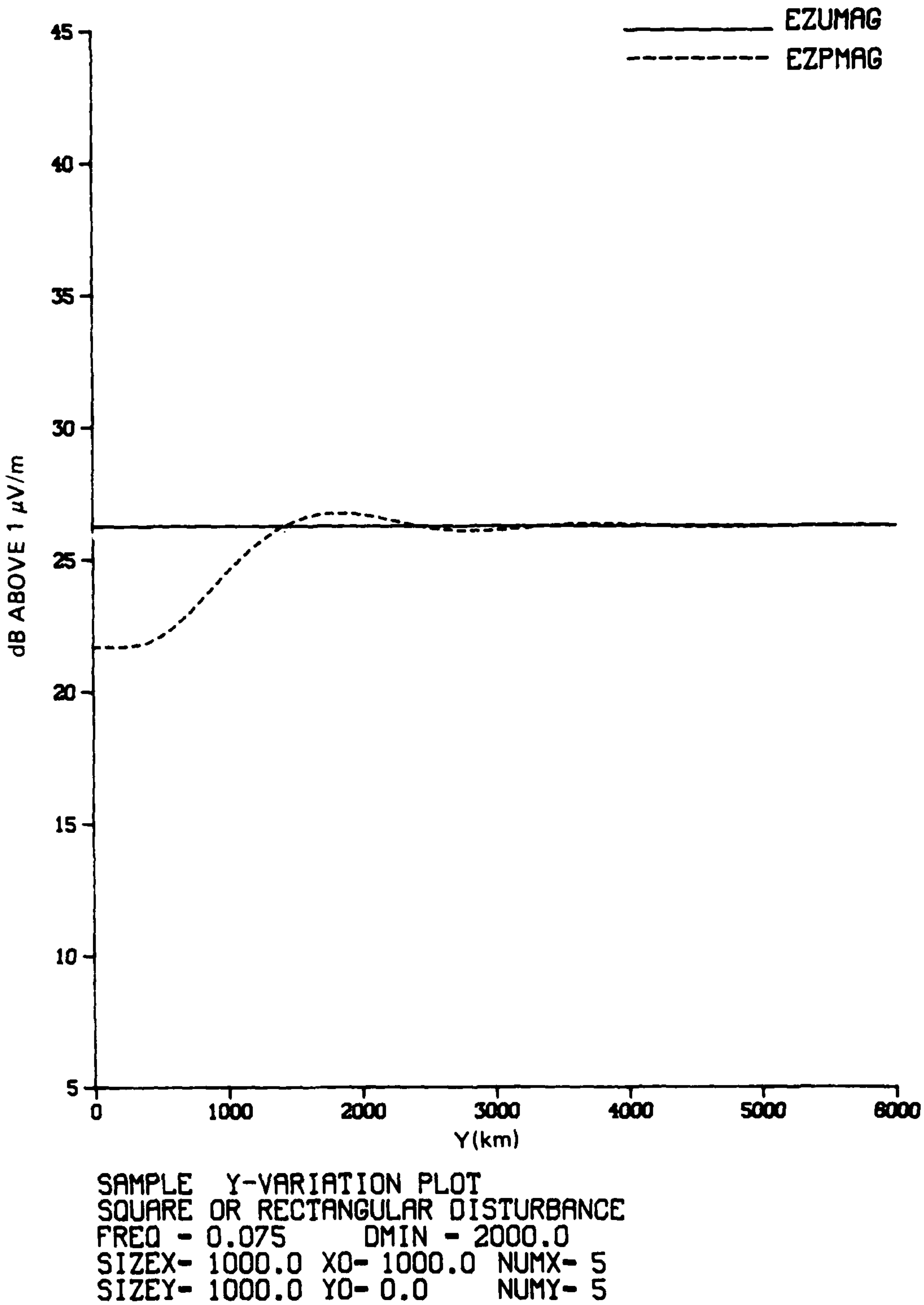


Figure 7. Sample y-variation plot for EZUMAG and EZPMAG assuming a rectangular disturbance.

## VI. PROGRAM CHECKS

Several program checks have been made of flat earth geometry cases which can be solved in terms of well known functions. In each case the disturbance is azimuthally symmetric with the transmitter located at the origin.

The first case considered is that of a uniform circular disturbance for which

$$S^2 = S_p^2 \quad \text{for } r<r_0 \tag{18}$$
$$S^2 = S_0^2 \quad \text{for } r>r_0$$

For this case the solution for the ratio of the disturbed lateral function, $\Psi$, to the undisturbed, $\Psi^i$ is for $r<r_0$

$$\frac{\Psi}{\Psi^i} = \frac{S_p}{S_0 H_1^{(2)}(kS_0 r)} \left\{ H_1^{(2)}(kS_p r) - \frac{\left(H_1^{(2)}(kS_p r_0)\ h(kS_0 r_0) - h(kS_p r_0)\ H_1^{(2)}(kS_0 r_0)\right)}{\left(J_1(kS_p r_0)\ h(kS_0 r_0) - j(kS_p r_0)\ H_1^{(2)}(kS_0 r_0)\right)} J_1(kSr) \right\} \tag{19}$$

and for $r>r_0$

$$\frac{\Psi}{\Psi^i} = \frac{S_p}{S_0} \left\{ \frac{H_1^{(2)}(kS_p r_0)\ j(kS_p r_0) - h(kS_p r_0)\ J_1(kS_p r_0)}{H_1^{(2)}(kS_0 r_0)\ j(kS_p r_0) - h(kS_0 r_0)\ J_1(kS_p r_0)} \right\} \tag{20}$$

In these equations

$$h(x) = \frac{x}{2} \left[H_0^{(2)}(x) - H_2^{(2)}(x)\right] \tag{21}$$

$$j(x) = \frac{x}{2} \left[J_0(x) - J_2(x)\right] \tag{22}$$

It is clear from equation (20) that $\psi/\psi^i$ is constant for $r > r_0$ as expected. Figure 8 shows the results calculated by using equation (19) along with the moment method results. The radius $r_0$ is 500 km. The unperturbed eigenangle is (83.985°,-34.909°) or equivalently $S_0$ = (1.185,-0.0681i) and the perturbed eigenangle is (59.393°,-65.552°) or equivalently $S_p$ =(1.488,-0.718i). $S_0$ is appropriate to a nighttime ambient ionosphere at 75 Hz, whereas, $S_p$ is appropriate to a nighttime ionosphere with a sporadic E layer[9]. The 13 x 13 mesh results give agreement to within a few hundreths of a dB of the exact results. In the moments method, the lateral function is calculated at the center points of each square mesh and the lateral function is linearly interpolated between those points. Because of approximations made in the slab containing the transmitter, the first meaningful data point obtained from the moment method is the first point to fall in a slab adjacent to that containing the transmitter. This explains the starting ranges for the moment method results.

A second check case considered is that of a circular disturbance which is uniform out to a radius $r_0$, then falls off as $1/r^2$ between $r_0$, and $r_1$, and is equal to $S_0$ beyond $r_1$. The mathematical description of S is

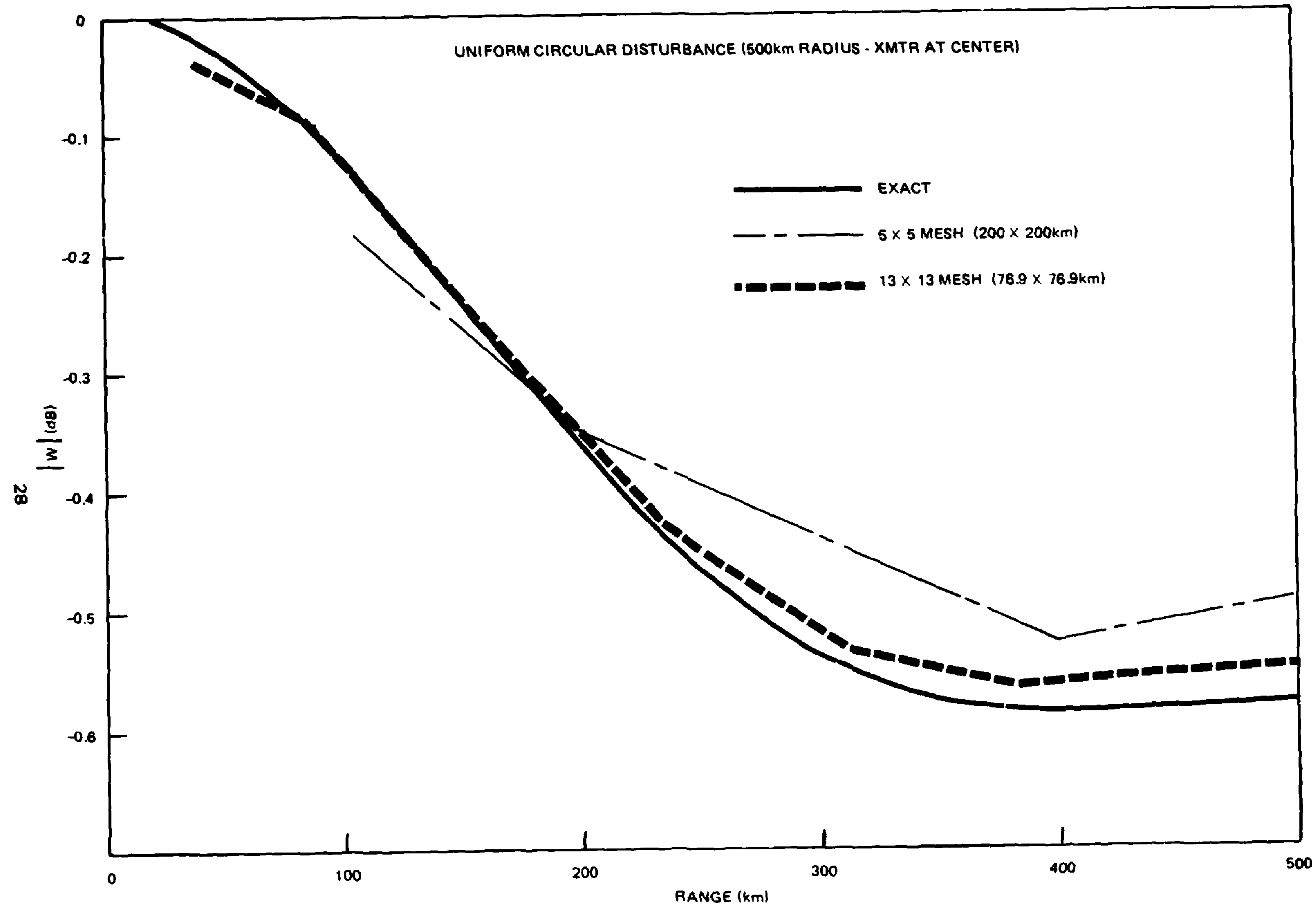


Figure 8. Comparison between analytic solution and the computer program output for problem 1: a uniform circular disturbance.

$$S^2 = S_p^2 \qquad ; r < r_0$$

$$S^2 = S_0^2 + (S_p^2 - S_0^2)\, r_0^2 / r^2 \qquad ; r_0 < r < r_1 \tag{23}$$

$$S^2 = S_0^2 \qquad ; r > r_1$$

When the transmitter is at the center of the disturbance the solution for the ratio of the disturbed lateral function, $\psi$ , to the undisturbed, $\psi^i$ , is for $r<r_0$

$$\frac{\psi}{\psi^i} = \frac{1}{S_0 H_1^{(2)}(kS_0 r)} \left[ S H_1^{(2)}(kS_p r) + a J_1(kS_p r) \right] \; ; \; r < r_0 \tag{24}$$

$$\frac{\psi}{\psi^i} = \frac{1}{S_0 H_1^{(2)}(kS_0 r)} \left[ b J_\nu(kS_0 r) + d J_{-\nu}(kS_0 r) \right] \; ; \; r_0 < r < r_1 \tag{25}$$

$$\frac{\psi}{\psi^i} = \frac{T}{S_0} \qquad ; \; r < r_1 \tag{26}$$

In these equations

$$\nu = \left[ 1 - \left(S_p^2 - S_0^2\right) \left(kr_0\right)^2 \right]^{1/2} \tag{27}$$

$$a = \frac{1}{\Delta} \begin{vmatrix} S H_1^{(2)}(kS_p r_0) & J_\nu(kS_0 r_0) & J_{-\nu}(kS_0 r_0) & 0 \\ S h_1(kS_p r_0) & j_\nu(kS_0 r_0) & j_{-\nu}(kS_0 r_0) & 0 \\ 0 & J_\nu(kS_0 r_1) & J_{-\nu}(kS_0 r_1) & -H_1^{(2)}(kS_0 r_1) \\ 0 & j_\nu(kS_0 r_1) & j_{-\nu}(kS_0 r_1) & -h_1(kS_0 r_1) \end{vmatrix} \tag{28}$$

$$b = \frac{1}{\Delta} \begin{vmatrix} -J_1(kS_p r_0) & SH_1^{(2)}(kS_p r_0) & J_{-\nu}(kS_0 r_0) & 0 \\ -j_1(kS_p r_0) & Sh_1(kS_p r_0) & j_{-\nu}(kS_0 r_0) & 0 \\ 0 & 0 & J_{-\nu}(kS_0 r_1) & -H_1^{(2)}(kS_0 r_1) \\ 0 & 0 & j_{-\nu}(kS_0 r_1) & -h_1(kS_0 r_1) \end{vmatrix} \tag{29}$$

$$d = \frac{1}{\Delta} \begin{vmatrix} -J_1(kS_p r_0) & J_{\nu}(kS_0 r_0) & SH_1^{(2)}(kS_p r_0) & 0 \\ -j_1(kS_p r_0) & j_{\nu}(kS_0 r_0) & Sh_1(kS_p r_0) & 0 \\ 0 & J_{\nu}(kS_0 r_1) & 0 & -H_1^{(2)}(kS_0 r_1) \\ 0 & j_{\nu}(kS_0 r_1) & 0 & -h_1(kS_0 r_1) \end{vmatrix} \tag{30}$$

$$T = \frac{1}{\Delta} \begin{vmatrix} -J_1(kS_p r_0) & J_{\nu}(kS_0 r_0) & J_{-\nu}(kS_0 r_0) & -SH_1^{(2)}(kS_p r_0) \\ -j_1(kS_p r_0) & j_{\nu}(kS_0 r_0) & j_{-\nu}(kS_0 r_0) & Sh_1(kS_p r_0) \\ 0 & J_{\nu}(kS_0 r_1) & J_{-\nu}(kS_0 r_1) & 0 \\ 0 & j_{\nu}(kS_0 r_1) & j_{-\nu}(kS_0 r_1) & -h_1(kS_0 r_1) \end{vmatrix} \tag{31}$$

$$\Delta = \begin{vmatrix} -J_1(kS_p r_0) & J_{\nu}(kS_0 r_0) & J_{\nu}(kS_0 r_0) & 0 \\ -j_1(kS_p r_0) & j_{\nu}(kS_0 r_0) & j_{-\nu}(kS_0 r_0) & 0 \\ 0 & J_{\nu}(kS_0 r_1) & J_{-\nu}(kS_0 r_1) & -H_1^{(2)}(kS_0 r_1) \\ 0 & j_{\nu}(kS_0 r_1) & j_{-\nu}(kS_0 r_1) & -h_1(kS_0 r_1) \end{vmatrix} \tag{32}$$

$$j_q(x) = \frac{x}{2} \left[ J_{q-1}(x) - J_{q+1}(x) \right] \tag{33}$$

$$h_q(k) = \frac{x}{2}\left[H^{(2)}_{q-1}(x) - H^{(2)}_{q+1}(x)\right] \qquad (34)$$

Again it is clear from equation (26) that $\psi/\psi^i$ is constant for $r > r_1$. Figure 9 shows results for $r_0$ = 300 km, $r_1$ = 1000 km and the same $S_0$ and $S_p$ used for the results of figure 8. The moment method results are for a 10 x 10 mesh and the results beyond 100 km agree with the exact values to better than a tenth of a dB.

A third check based on the model described by equations (23) is shown in figure 10. $S_0$ and $S_p$ are assigned the same values as for figure 8; however, $r_0$ has been taken equal to 588 km and $r_1$ = 2000 km. The moment method result is for a 17 x 17 mesh which is the largest the program can handle because of storage limitations. The mesh size in this instance is approximately 235 km. In this connection Hagmann et al[13], state that the mesh size must be less than 155 $\lambda_0$ where $\lambda_0$ is the unperturbed wavelength. In the present case of 75 Hz, $\lambda_0 \simeq 4000/S_{0r} \simeq 3375$ km . This would give a maximum cell size of $\simeq$ 523 km. It has been our experience that approaching this limit leads to substantial error and it would probably be best at 75 Hz not to exceed mesh sizes of several hundred kilometers. This would limit the linear dimension of the disturbance to something on the order of 5000 km at 75 Hz. Figure 10 shows the agreement between the exact calculation and the moment method to be within a few tenths of a dB. It is also very likely true that the cases checked are some of the most difficult for the moment method to handle because the gradient of the incident field is largest close to the transmitter. Thus, it would be expected that for disturbances remote from the transmitter better accuracy would be obtained for the same mesh size.

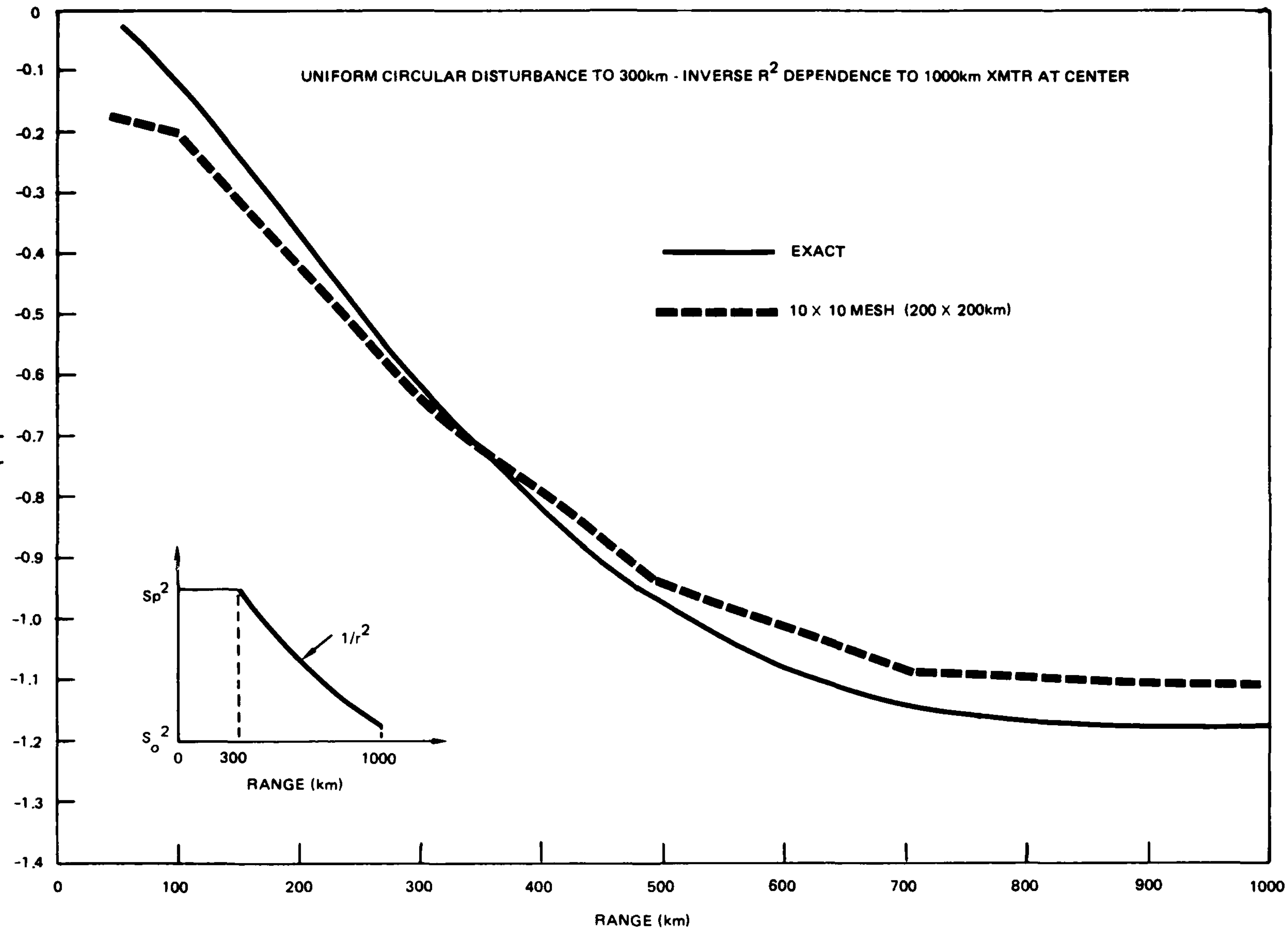


Figure 9. Comparison between analytic solution and the computer program output for problem 2: a uniform circular disturbance to $r_0$ with an inverse $r^2$ dependence of $S_p$ between $r_0$ and $r_1$ using a 10 X 10 mesh.

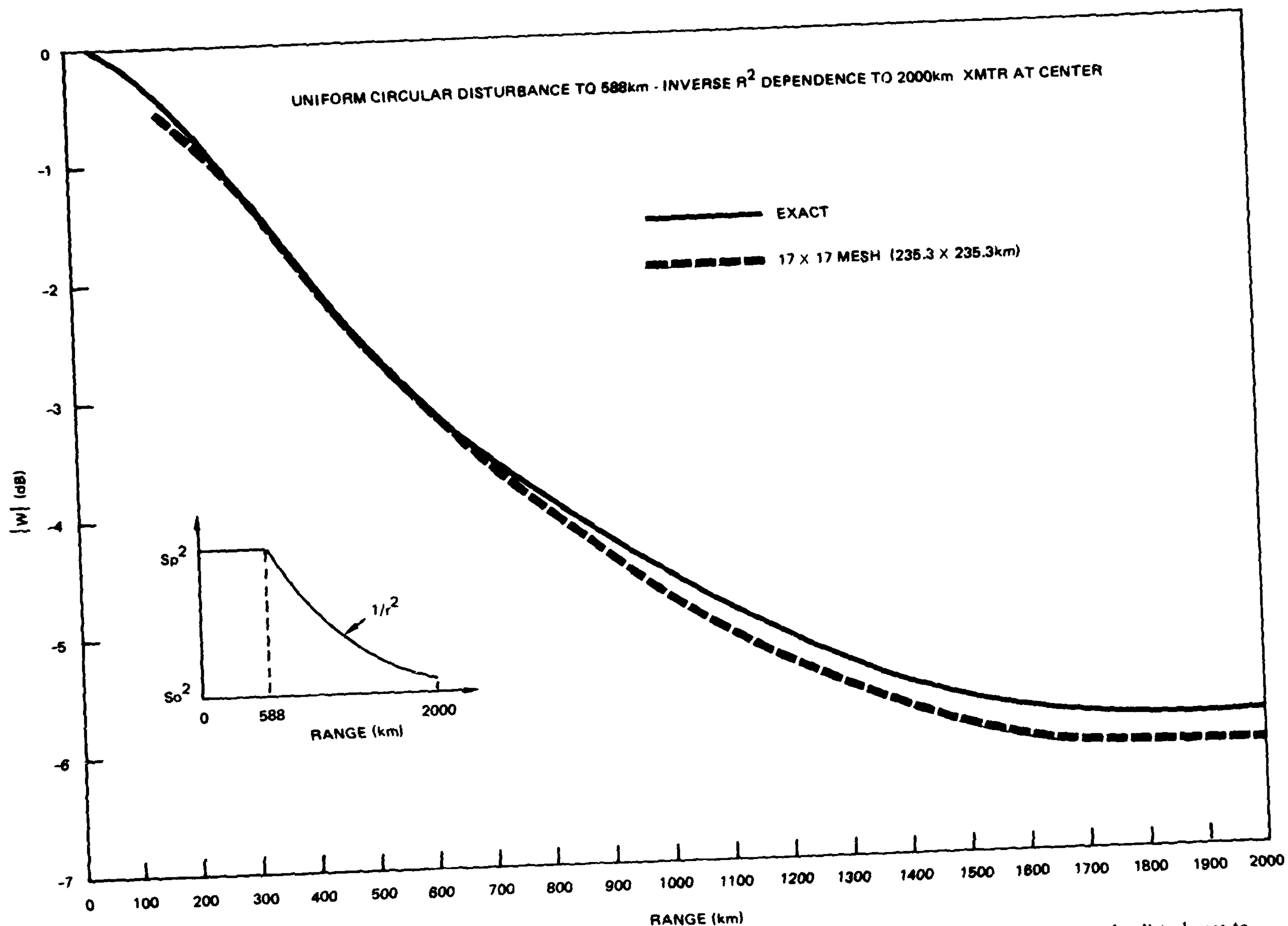


Figure 10. Comparison between analytic solution and the computer program output for problem 3: a uniform circular disturbance to $r_0$ with an inverse $r^2$ dependence of $S_p$ between $r_0$ and $r_1$ using a 17 X 17 mesh.

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# VIII. APPENDIX: PROGRAM LISTING

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```
@FTN,USFO    SPORAD.MAIN
FTN 10R1A  09/22/82-11:32(9,10)
      C
      C        SPORADIC-E PROGRAM FOR ELF
      C
               IMPLICIT COMPLEX   (A-H,O-Z)
      C
               PARAMETER MAXNX=12,NDIM=100,NRPTS=500
      C
      C        MAXNX IS THE MAX NUMBER OF DISTURBED EIGENS WHICH CAN BE INPUT
      C        NDIM IS THE MAX VALUE OF NUMX*NUMY
      C        NRPTS IS THE MAX  NUMBER OF POINTS TO PLOT
      C
               COMPLEX     IM/(0.E0,1.E0)/,J1,J2,NGXIM,KSO,NGSQ,
              $            A(NDIM,NDIM),
              $            EZO(NDIM),EZS(NDIM),SD(NDIM),XTRD(NDIM),WI(NDIM),
              $            SI(MAXNX),XTRI(MAXNX)
      C
               REAL        XM,YM,XGSQ,AI,SIZEX,SIZEY,XDINC,XO,YO,YOVERX,DELTAX,
              $            DELTAY,X1,Y1,XINC,YINC,EPSR,RHOMN,EZREL,EZANG,KA,DELY,
              $            YMAX,F,WMAG,WANG,YMID,OMEGA,RADIUS,WAVENO,FREQ,SIGMA,
              $            ERR,DIST,DMIN,DM,DELD,DMAX,HXINC,HYINC,RG,AIMAX,DST,
              $            RGMAX,RGMIN,EZUMAG,EZUANG,EZPMAG,EZPANG,PI,DTR,EPSO,
              $            XG(4),YG(4),
              $            X(NDIM),Y(NDIM),CLNQ(NDIM),XX(NDIM),YY(NDIM),
              $            XI(MAXNX),YI(MAXNX),
              $            XPLOT(NRPTS),Y1PLOT(NRPTS),Y2PLOT(NRPTS),Y3PLOT(NRPTS),
              $            EXTIC,EYTIC,WXTIC,WYTIC,XMAX,XLNG,YLNG,WMIN,WMAX,EMIN,
              $            EMAX
      C
               INTEGER     IROW(NDIM)
      C
               CHARACTER*1 LABELO/'?'/
               CHARACTER*4 ID(20)
               CHARACTER*5 LABEL1/'    ?'/,  LABEL2/'____?'/,LABEL3/'____ '/
               CHARACTER*8 XLABEL
               CHARACTER*36 LABEL
      C
               COMMON/ONE/H12,H22,J1,J2,SO,ARGO,KA,KSO
               COMMON/LABELS/ID,LABEL,XLABEL
               COMMON/INPUT/FREQ,DMIN,DMAX,SIZEX,SIZEY,XO,YO,EXTIC,EYTIC,WXTIC,
              $               WYTIC,XLNG,YLNG,EMIN,EMAX,WMIN,WMAX,XMAX,NUMX,NUMY,
              $               IFLAG
               COMMON/PLDATA/XPLOT,Y1PLOT,Y2PLOT,Y3PLOT,NPTS
      C
      C        DM - DIPOLE MOMENT IN AMPERE-METERS
      C        DMIN - MINIMUM RANGE (KM) FOR DISTANCE VARIATION
      C        DMAX - MAXIMUM RANGE (KM) FOR DISTANCE VARIATION
      C        DELD - INCREMENT (KM) FOR DISTANCE VARIATION
      C        YMAX - MAXIMUM OFF-AXIS VALUE (KM) FOR Y VARIATION
      C        DELY - INCREMENT (KM) FOR Y VARIATION
      C        IFLAG=1  Y VARIATION
      C        IFLAG=2  DIST VARIATION
      C        IGRID = 0  SQUARE OR RECTANGULAR DISTURBANCE
      C        IGRID = 1  CIRCULAR OR ELLIPTICAL DISTURBANCE
      C        XO,YO - COORDINATES (KM) AT CENTER OF DISTURBANCE
      C                YO IS ALSO INITIAL VALUE FOR Y VARIATION
```

```
    C     NUMX,NUMY - THE DISTURBANCE IS DIVIDED INTO NUMX GRIDS IN THE
    C                 X DIRECTION AND NUMY GRIDS IN THE Y DIRECTION
    C     SIZEX,SIZEY - DEFINES THE PHYSICAL SIZE OF THE DISTURBANCE - IT IS
    C                   SIZEX KM BY SIZEY KM
    C     IPLOT=0  DON'T PLOT
    C     IPLOT=1  PLOT
    C     XLNG,YLNG - LENGTH (INCHES) OF X-AXIS AND Y-AXIS RESPECTIVELY
    C     WMIN,WMAX - MINIMUM AND MAXIMUM (DB) FOR Y-AXIS OF WMAG PLOT
    C     EMIN,EMAX - MINIMUM AND MAXIMUM (DB) FOR Y-AXIS OF EZ PLOT
    C     EXTIC,EYTIC - UNITS PER TIC MARK ALONG X AND Y AXIS RESPECTIVELY
    C                   FOR EZ PLOTS
    C     WXTIC,WYTIC - UNITS PER TIC MARK ALONG X AND Y AXIS RESPECTIVELY
    C                   FOR WMAG PLOTS
    C
          NAMELIST/DATUM/DM,DMIN,DMAX,DELD,YMAX,DELY,IFLAG,IGRID,
         $                XO,YO,NUMX,NUMY,SIZEX,SIZEY,IPLOT,XLNG,YLNG,
         $                WMIN,WMAX,EMIN,EMAX,EXTIC,EYTIC,WXTIC,WYTIC
    C
          DATA IPLOT/0/
          DATA PI/3.14159265358979E0/,DTR/.017453292E0/,EPS0/8.85434E-12/
          DATA XLNG/5./,YLNG/6./,WMIN/-6./,WMAX/2./,EMIN/-6./,EMAX/2./
          DATA EXTIC/200./,EYTIC/5./,SIZEX/1.E3/,SIZEY/1.E3/
          DATA WXTIC/200./,WYTIC/1./
          DATA DMIN/25.E0/,DMAX/1000.E0/,DELD/25.E0/
          DATA YMAX/500.E0/,DELY/25.E0/,XO/0.E0/,YO/0.E0/
          DATA DM/6.75E6/
          DATA IFLAG/2/,IGRID/0/
          DATA CONST/(-.707106781186548E0,-.707106781186548E0)/
    C
    C
          DEFINE CAPG2(ARG) = PI/(2.0E0* SIN(ARG/6371.0E0))
    C
          PRINT 915
          READ(5,DATUM)
          WRITE(6,DATUM)
    C
          NU = NUMX*NUMY
          IF(NU .GT. NDIM)
         $   THEN
1                PRINT 971
1                STOP
1         ENDIF
          NPTS = 0
          DIST = DMIN
          YMID = YO
    C
    C     SET UP DISTURBED REGION GRID
          XINC = SIZEX/NUMX
          HXINC = .5*XINC
          YINC = SIZEY/NUMY
          HYINC = .5*YINC
    C
    C     GRID ELEMENTS MUST BE SQUARE
          IF(XINC .NE. YINC)
         $   THEN
1                PRINT 976
1                STOP
```

```
1           ENDIF
            YOVERX = SIZEY/SIZEX
            X1 = X0-0.5E0*(SIZEX-XINC)
            Y1 = Y0+0.5E0*(SIZEY-YINC)
            RADIUS = SQRT((XINC*YINC)/PI)
            XX(1) = X1
            DO 12 I=2,NUMX
1     12    XX(I) = XX(I-1)+XINC
            YY(1) = Y1
            DO 13 J=2,NUMY
1     13    YY(J) = YY(J-1)-YINC
            M = 0
            DO 15 J=1,NUMY
1           DO 15 I=1,NUMX
2           M = M+1
2           X(M) = XX(I)
2           Y(M) = YY(J)
2     15    CONTINUE
2     C
2     C     PRINT SCHEMATIC OF DISTURBED REGION GRID
            IF(NUMY .GT. 10) PRINT 915
            PRINT 920
            PRINT 930,(LABEL3,J=1,NUMX)
            DO 18 K=1,NUMY
1           PRINT 910,LABEL0,(LABEL1,J=1,NUMX)
1           PRINT 940,LABEL0,((K-1)*NUMX+J,LABEL0,J=1,NUMX)
1           PRINT 910,LABEL0,(LABEL1,J=1,NUMX)
1           PRINT 910,LABEL0,(LABEL2,J=1,NUMX)
1     18    CONTINUE
1     C
1     C     PRINT COORDINATES OF GRID
            PRINT 920
            N = 1
            WRITE(6,100) N,X(N),Y(N)
            WRITE(6,100) NUMX,X(NUMX),Y(NUMX)
            N = NU-NUMX+1
            WRITE(6,100) N,X(N),Y(N)
            WRITE(6,100) NU,X(NU),Y(NU)
      C
      C     READ GRID DATA
      C
      C     MODE PARAMETERS ARE FROM USING NPUNCH=1 IN
      C     THE WAVEGUID OR MODESRCH COMPUTER PROGRAMS
            READ 1000,ID
            PRINT 1001,ID
      C
      C     AMBIENT
            READ 1010,FREQ,SIGMA,EPSR
            PRINT 1011,FREQ,SIGMA,EPSR
            OMEGA=6.28318530717959E3*FREQ
            WAVENO = .020958445E0*FREQ
            NGSQ = SIGMA/(IM*OMEGA*EPS0)+EPSR
            NGXTM = C SQRT(NGSQ)
            IF(DREAL(NGXTM) .LT. 0.0E0) NGXTM=-NGXTM
            EX0 = 1.0E0/NGXTM
            ECONST= .03248E6*DM*EX0*WAVENO**2/(5.0E3* SQRT(FREQ))
            N = 0
```

```
         PRINT 1009
         READ 1020,THETAO,TMP1
         THTAO = THETAO*DTR
         SO = C SIN(THTAO)
         CSQ = (1.EO,0.EO)-SO**2
         C = C SQRT(CSQ)
         SQROOT = C SQRT(NGSQ-CSQ)
         XTRAO = -4.0*TMP1*SO
         PRINT 1021,N,THETAO,XTRAO
         KA = WAVENO*RADIUS
         KSO = WAVENO*SO
         ARGO = KSO*RADIUS
         CALL CBESJY(ARGO,1,BJ,BY,0,0)
         H12 = BJ- IM*BY
         J1 = BJ
         CALL CBESJY(ARGO,2,BJ,BY,0,0)
         H22 = BJ-IM*BY
         J2 = BJ
C
C        DISTURBED
25       READ 1010,F
         IF(F .NE. 0.)
        $   THEN
               N = N+1
               IF(N .EQ. MAXNX)
        $         THEN
                     PRINT 974
                     STOP
               ENDIF
               READ 1020,THETAP,TMP1
               THTAP = THETAP*DTR
               SP = C SIN(THTAP)
               XTRAP=-4.0*TMP1*SP
               PRINT 1021,N,THETAP,XTRAP
               SI(N) = SP
               XTRI(N) = XTRAP
               GO TO 25
            ELSE
               NMAX = N
         END IF
C
         IF(NMAX .EQ. 1)
        $   THEN
C              UNIFORM DISTURBANCE
               NMAX = 2
               SI(2) = SP
               XTRI(2) = XTRAP
         ENDIF
C
C        SET UP INTERPOLATION ARRAYS
         XDINC = 0.5EO*SIZEX/(NMAX-1)
         DO 33 N=1,NMAX
         XI(N) = XDINC*(N-1)
33       YI(N) = YOVERX*XI(N)
C
C        FILL GRID OF SD AND XTRD
         IF(IGRID .EQ. 0)
```

```
              $    THEN
         C              SQUARE OR RECTANGLE
         C
         C              A RECTANGLE CAN ONLY BE UNIFORMLY DISTURBED
         C              A SQUARE CAN HAVE A NON-UNIFORM DISTURBANCE
1                       LABEL = 'SQUARE OR RECTANGULAR DISTURBANCE    '
1                       DO 39 M=1,NU
2                       XM =  ABS(X(M)-XO)
2                       YM =  ABS(Y(M)-YO)
2                       IF(XM .GT. .5E0*SIZEX .OR. YM .GT. .5E0*SIZEY)
2             $            THEN
3                             SD(M) = SO
3                             XTRD(M) = XTRAO
3                          ELSE
3                             I = 1
3                             K = 1
3        C
3        35                   IF(XM .LE. XI(I+1)) GO TO 37
3                             I = I+1
3                             GO TO 35
3        37                   IF(YM .LE. YI(K+1)) GO TO 38
3                             K = K+1
3                             GO TO 37
3        38                   IF(I .GT. K)
3             $                  THEN
4                                   SLOPE = (XM-XI(I))/(XI(I+1)-XI(I))
4                                   SD(M) = SI(I)+(SI(I+1)-SI(I))*SLOPE
4                                   XTRD(M) = XTRI(I)+(XTRI(I+1)-XTRI(I))*SLOPE
4                                ELSE
4                                   SLOPE = (YM-YI(K))/(YI(K+1)-YI(K))
4                                   SD(M) = SI(K)+(SI(K+1)-SI(K))*SLOPE
4                                   XTRD(M) = XTRI(K)+(XTRI(K+1)-XTRI(K))*SLOPE
4                             ENDIF
3                       ENDIF
3        C
2        39             CONTINUE
2        C
1                  ELSE
1        C              ELLIPSE OR CIRCLE
1                       LABEL = 'CIRCULAR OR ELLIPTICAL DISTURBANCE   '
1                       AIMAX = XI(NMAX)
1                       DO 59 M=1,NU
1        C              COORDS OF CENTER OF GRID RELATIVE TO CENTER OF DISTURBANCE
2                       XM = X(M)-XO
2                       YM = Y(M)-YO
2        C              COORDS OF CORNERS OF GRID
2                       XG(1) = XM-HXINC
2                       XG(2) = XM+HXINC
2                       XG(3) = XG(1)
2                       XG(4) = XG(2)
2                       YG(1) = YM+HYINC
2                       YG(2) = YG(1)
2                       YG(3) = YM-HYINC
2                       YG(4) = YG(3)
2                       RGMAX = -1.0E6
2                       RGMIN =  1.0E6
2                       DO 45 I=1,4
```

```
2   C           RANGE OF EACH CORNER FROM CENTER OF DISTURBANCE
3               RG    =  SQRT(XG(I)**2+(YG(I)/YOVERX)**2)
3               RGMAX = AMAX1(RGMAX,RG)
3   45          RGMIN = AMIN1(RGMIN,RG)
2               IF(RGMIN .GE. AIMAX)
2         $        THEN
2   C                   GRID IS COMPLETELY OUTSIDE OF DISTURBANCE
3                       SD(M) = SO
3                       XTRD(M) = XTRAO
3                  ELSE
3                       IF(RGMAX .LE. AIMAX)
3         $                THEN
3   C                          GRID IS COMPLETELY INSIDE OF DISTURBANCE
4                              I = 1
4                              AI =  SQRT(XM**2+(YM/YOVERX)**2)
4   50                         IF(AI .LE. XI(I+1)) GO TO 51
4                              I = I+1
4                              GO TO 50
4   51                         SLOPE = (AI-XI(I))/(XI(I+1)-XI(I))
4                              SD(M) = SI(I)+(SI(I+1)-SI(I))*SLOPE
4                              XTRD(M) = XTRI(I)+(XTRI(I+1)-XTRI(I))*SLOPE
4                          ELSE
4   C                          GRID IS ON BORDER OF THE DISTURBANCE
4   C                          DIVIDE GRID INTO 16 SUBSQUARES
4                              DELTAX = XINC/8.
4                              DELTAY = YINC/8.
4                              XG(1) = (XM-DELTAX*3.)**2
4                              XG(2) = (XM-DELTAX    )**2
4                              XG(3) = (XM+DELTAX    )**2
4                              XG(4) = (XM+DELTAX*3.)**2
4                              YG(1) = ((YM+DELTAY*3.)/YOVERX)**2
4                              YG(2) = ((YM+DELTAY    )/YOVERX)**2
4                              YG(3) = ((YM-DELTAY    )/YOVERX)**2
4                              YG(4) = ((YM-DELTAY*3.)/YOVERX)**2
4   C                          COUNT NUMBER OF SUBSQUS WITHIN DISTURBANCE
4                              N = 0
4                              DO 55 I=1,4
5                              XGSQ = XG(I)
5                              DO 55 J=1,4
6                              RG =  SQRT(XGSQ+YG(J))
6   55                         IF(RG .LE. AIMAX) N=N+1
4                              SLOPE = N/16.
4                              SD(M) =  SO+(SI(NMAX)-SO)*SLOPE
4                              XTRD(M) = XTRAO+(XTRI(NMAX)-XTRAO)*SLOPE
4                       ENDIF
3               ENDIF
2   39          CONTINUE
1          ENDIF
1   C
1   C      SET UP A
           DO 55 M=1,NU
1          DO 65 N=1,NU
2   65     A(M,N) = CAPA(SD(N),SQRT((X(M)-X(N))**2+(Y(M)-Y(N))**2))
2   C
    70     MGRID = 0
           DO 79 M= 1,NU
1          NGRID = 0
```

```
1           XM = X(M)
1           YM = Y(M)
1           IF(XM+  HXINC .LT. 0.0E0 .OR. XM-  HXINC .GE. 0.0E0 .OR.
1          $   YM+  HYINC .LT. 0.0E0 .OR. YM-  HYINC .GE. 0.0E0) GO TO 75
1     C     XMIR IS INSIDE GRID
1     C     GRID POINT IS DISTURBED
1           XG(1) = XM-.25*XINC
1           XG(3) = XG(1)
1           XG(2) = XM+.25*XINC
1           XG(4) = XG(2)
1           YG(1) = YM+.25*YINC
1           YG(2) = YG(1)
1           YG(3) = YM-.25*YINC
1           YG(4) = YG(3)
1           MGRID = M
1           PRINT 955,M
1           NQUAD = 0
1           SUM = 0.0E0
1     71    NQUAD = NQUAD+1
1           IF(XG(NQUAD)+.125*XINC .GE. 0.0E0 .AND.
1          $   XG(NQUAD)-.125*XINC .LT. 0.0E0 .AND.
1          $   YG(NQUAD)+.125*YINC .GE. 0.0E0 .AND.
1          $   YG(NQUAD)-.125*YINC .LT. 0.0E0) GO TO 71
1           NGRID = NGRID+1
1           XM = XG(NQUAD)
1           YM = YG(NQUAD)
1     75    RHOMN =   SQRT(XM**2+YM**2)
1           ARGU = KS0*RHOMN
1           CALL CBESJY(ARGU,1,BJ,BY,0,0)
1           H12 = BJ-IM*BY
1           IF(XM .EQ. 0.0E0) XM=1.0E-6
1           EZ0(M) = C SQRT(ARGU*CAPG2(RHOMN))*CONST*H12*XM/RHOMN
1           IF(NGRID .EQ. 0) GO TO 78
1           SUM = SUM+EZ0(M)
1           IF(NQUAD .LT. 4) GO TO 71
1           EZ0(M) = SUM/NGRID
1     78    IF(C ABS(EZ0(M)) .LE. 1.0E-6) EZ0(M)=1.0E-21
1     79    CONTINUE
1     C
1     C     PRINT TABLE OF EZ0
            WRITE (6,110) YMID
            WRITE (6,113)
            DO 81 I=1,NUMY
1           WRITE(6,112) (C ABS(EZ0(NUMX*(I-1)+J)),J=1,NUMX)
1     81    CONTINUE
1     C
1     C     SOLVE FOR SCATTERED FIELDS
            CALL CLINEQ(A,EZ0,EZS,IROW,CLNQ,NU,NDIM,NPTS,ERR)
      C
      C     PRINT TABLE OF EZS
            WRITE (6,111)
            DO 83 I=1,NUMY
1           WRITE(6,112) (C ABS(EZS(NUMX*(I-1)+J)),J=1,NUMX)
1     83    CONTINUE
1     C
            DO 85 M=1,NU
1           RATIO = EZS(M)/EZ0(M)
```

```
1            IF(MGRID .EQ. M) RATIO=1.0
1            WI(M) = C LOG(RATIO)
1      85    CONTINUE
1      C
1      C     PRINT TABLE OF WI
             WRITE(6,102)
             DO 87 I=1,NUMY
1            WRITE(6,103) (REAL(WI(NUMX*(I-1)+J))*8.686,J=1,NUMX)
1      87    CONTINUE
1      C
             WRITE (6,950)
             DIST = DMIN
       90    NPTS = NPTS+1
             IF(NPTS .GT. NRPTS)
            $   THEN
                    PRINT 973
1                   STOP
1            ENDIF
1      C
             ARGU = KSO*DIST
             CALL CBESJY(ARGU,1,BJ,BY,0,0)
             H12 = BJ-IM*BY
             EZU = C SQRT(ARGU*CAPG2(DIST))*CONST*H12
             IF(XX(1)-HXINC .GE. DIST .OR. XX(NUMX)+HXINC .LE. DIST .OR.
            $   YY(1)+HYINC .LE. 0.E0 .OR. YY(NUMY)-HYINC .GE. 0.E0)
            $   THEN
       C            RCVR IS OUTSIDE OF DISTURBED AREA
1                   XTRA2 = XTRAO
1                   SUM = (0.0E0,0.0E0)
1                   DO 95 N=1,NU
2                   RHOMN = SQRT((DIST-X(N))**2+Y(N)**2)
2                   SUM = SUM+CAPA(SD(N),RHOMN)*EZS(N)
2      95           CONTINUE
1                   EZ = EZU-SUM
1                   RATIO = EZ/EZU
1                   WMAG = 20.0E0*ALOG10(C ABS(RATIO))
1                   WANG = C ANG(RATIO)
1               ELSE
1      C            RCVR IS IN DISTURBED AREA
1                   I = 1
1                   DO 96 J=1,NUMX
2                   IF(XX(J)-HXINC .LT. DIST .AND. DIST .LE. XX(J)+HXINC)
2           $       GO TO 97
2                   I = I+1
2      96           CONTINUE
1      97           K = 1
1                   DO 98 J=1,NUMY
2                   IF(YY(J)-HYINC .LT. 0.E0 .AND. 0.E0 .LE. YY(J)+HYINC)
2           $       GO TO 99
2                   K = K+1
2      98           CONTINUE
1      99           M = (K-1)*NUMX+I
1                   XTRA2 = XTRD(M)
1                   EZ = EZU
1                   IF(M .EQ. MGRID) GO TO 130
1                   IF(I .GT. 1) GO TO 120
1                   N1 = M
```

```
1                          N2 = M+1
1                          IF(K .GT. 1) GO TO 106
1      105                 N3 = N1+NUMX
1                          N4 = N3+1
1                          GO TO 125
1      106                 IF(K .EQ. NUMY) GO TO 108
1      107                 IF(YY(K) .GE. 0.) GO TO 109
1      108                 N3 = N1-NUMX
1                          N4 = N3+1
1                          GO TO 125
1      109                 N3 = N1+NUMX
1                          N4 = N3+1
1                          GO TO 125
1      120                 IF(I .LT. NUMX) GO TO 122
1                          N1 = M-1
1                          N2 = M
1      121                 IF(K .EQ. 1)  GO TO 105
1                          IF(K .EQ. NUMY) GO TO 108
1                          GO TO 107
1      122                 IF(XX(I) .LE. DIST) GO TO 123
1                          N1 = M-1
1                          N2 = M
1                          GO TO 121
1      123                 N1 = M
1                          N2 = M+1
1                          GO TO 121
1      125                 SLOPE = -Y(N1)/(Y(N3)-Y(N1))
1                          W1 = WI(N1)+(WI(N3)-WI(N1))*SLOPE
1                          W2 = WI(N2)+(WI(N4)-WI(N2))*SLOPE
1                          IF(I .EQ. NUMX .AND. DIST .GT. X(N2) .OR.
1             $               I .EQ. 1    .AND. DIST .LT. X(N1))
1             $               THEN
2                                    IF(I .EQ. 1)
2             $                         THEN
3                                               DST = X0-.5*SIZEX
3                                               DELTAX = HXINC
3                                               W2 = W1
3                                               N2 = N1
3                                       ELSE
3                                               DST = X0+.5*SIZEX
3                                               DELTAX = -HXINC
3                                    ENDIF
2                                    ARGU = KS0*DST
2                                    CALL CBESJY(ARGU,1,BJ,BY,0,0)
2                                    H12 = BJ-IM*BY
2                                    EZ1 = C SQRT(ARGU*CAPG2(DST))*CONST*H12
2                                    SUM = (0.0E0,0.0E0)
2                                    DO 126 N=1,NU
3                                    RHOMN = SQRT((DST -X(N))**2+Y(N)**2)
3                                    SUM = SUM+CAPA(SD(N),RHOMN)*EZS(N)
3      126                           CONTINUE
2                                    W1 = CLOG((1.0,0.0)-SUM/EZ1)
2                                    RATIO = W1+(W2-W1)*(DIST-DST)/DELTAX
2                             ELSE
2                                    RATIO = W1+(W2-W1)*((DIST-X(N1))/XINC)
2                          ENDIF
1                          WMAG = REAL(RATIO)*8.686
```

```
1                 WANG = AIMAG(RATIO)
1                 EZ = C EXP(RATIO)*EZU
1           ENDIF
1    C
1    C
     130    IF(MGRID .EQ. 0)
           $    THEN
     C                XMTR IS OUTSIDE OF DISTURBED AREA
1                 XTRA1 = XTRAO
1               ELSE
1    C                XMTR IS IN DISTURBED AREA
1                 XTRA1 = XTRD(MGRID)
1           ENDIF
1    C
            EZUABS =ECONST*EZU*XTRAO
            EZPABS =ECONST*EZ*C SQRT(XTRA1*XTRA2)
            RATIO = EZPABS/EZUABS
            EZREL = 20.0E0*ALOG10(C ABS(RATIO))
            EZANG = C ANG(RATIO)
            EZUMAG = 20.0E0*ALOG10(C ABS(EZUABS))
            EZUANG = C ANG(EZUABS)
            EZPMAG = 20.0E0*ALOG10(C ABS(EZPABS))
            EZPANG = C ANG(EZPABS)
            WRITE (6,960) YMID,DIST,WMAG,WANG,EZREL,EZANG,
           $                EZUMAG,EZUANG,EZPMAG,EZPANG
            Y1PLOT(NPTS) = WMAG
            Y2PLOT(NPTS) = EZUMAG
            Y3PLOT(NPTS) = EZPMAG
            IF(IFLAG .EQ. 2) GO TO 140
     C
     C      Y VARIATION
            DO 131 N = 1,NU
1    131    Y(N) = Y(N)+DELY
            DO 132 J=1,NUMY
1    132    YY(J) = YY(J)+DELY
            XPLOT(NPTS) = YMID
            XLABEL = ' Y(KM)   '
            YMID = YMID+DELY
            IF(YMID  .LE. YMAX) GO TO 70
            XMAX = YMAX
            IF(IPLOT .EQ. 1) GO TO 800
            STOP
     C
     C      DISTANCE VARIATION
     140    XPLOT(NPTS) = DIST
            XLABEL = ' X(KM)   '
            DIST = DIST + DELD
            IF(DIST .LE. DMAX) GO TO 90
            XMAX = DMAX
            IF(IPLOT .EQ. 1) GO TO 800
            STOP
     C
     C      PLOTTING
     800    CALL DBPLOT
     C
     100    FORMAT(' COORDINATES AT CENTER OF MESH NUMBER ',I3,' ARE:  X=',
           $  F8.2,' Y=',F8.2)
```

```
102   FORMAT(/,10X,'WI')
103   FORMAT(1X,13F10.4)
110   FORMAT(1H0,'YMID = ',F12.2)
111   FORMAT(/,10X,'EZS')
112   FORMAT((1X,(1P13E10.2)))
113   FORMAT(/,10X,'EZO')
910   FORMAT(20X,A1,13A5)
915   FORMAT('1')
920   FORMAT('0')
930   FORMAT(21X,13A5)
940   FORMAT (20X,A1,13(I3,1X,A1))
950   FORMAT(/,4X,'YMID',5X,'DIST',6X,' WMAG ',8X,' WANG ',8X,' EZREL',
     $ 8X,' EZANG',8X,'EZUMAG',8X,'EZUANG',8X,'EZPMAG',8X,'EZPANG')
955   FORMAT('OXMTR IS INSIDE GRID ',I3)
960   FORMAT(2(2X,F7.1),8(2X,1PE12.5))
971   FORMAT(' NU = NUMX*NUMY IS GREATER THAN PARAMETER VARIABLE NDIM')
972   FORMAT(' NMAX DOES NOT EQUAL NU OR 1')
973   FORMAT(' NUMBER OF POINTS PLOTTED IS GREATER THAN PARAMETER VARIAB
     $LE NRPTS')
974   FORMAT(' N IS GREATER THAN PARAMETER VARIABLE MAXNX')
976   FORMAT(' XINC MUST EQUAL YINC')
1000  FORMAT(20A4)
1001  FORMAT('1',20A4)
1009  FORMAT(2X,'GRID',6X,'THETA',25X,'XTRA')
1010  FORMAT(10X,E8.0,34X,E10.0,2X,E5.0)
1011  FORMAT(' FREQ = ',E10.3,' SIGMA = ',E10.3,' EPSR=',F7.2)
1020  FORMAT(1X,2F9.0,1X,2E15.0//)
1021  FORMAT(1X,I3,2F10.5,2X,1P2E18.9)
      END
```

END FTN 2678 IBANK 22972 DBANK 2068 COMMON

```
      SUBROUTINE DBPLOT
      PARAMETER NRPTS=500
      CHARACTER*8 XLABEL
      CHARACTER*36 LABEL
      CHARACTER*4 ID(20)
      DIMENSION XPLOT(NRPTS),Y1PLOT(NRPTS),Y2PLOT(NRPTS),Y3PLOT(NRPTS)
      COMMON/LABELS/ID,LABEL,XLABEL
      COMMON/INPUT/FREQ,DMIN,DMAX,SIZEX,SIZEY,X0,Y0,EXTIC,EYTIC,WXTIC,
     $             WYTIC,XLNG,YLNG,EMIN,EMAX,WMIN,WMAX,XMAX,NUMX,NUMY,
     $             IFLAG
      COMMON/PLDATA/XPLOT,Y1PLOT,Y2PLOT,Y3PLOT,NPTS
      CALL BGNPL(1)
      CALL PHYSOR(2.0,2.0)
      CALL TITLE(' ',1,XLABEL,8,'WMAG(DB)',8,XLNG,YLNG)
      CALL INTAXS
      CALL YAXANG(0.0)
      CALL GRAF(0.,WXTIC,XMAX,WMIN,WYTIC,WMAX)
      CALL CURVE(XPLOT,Y1PLOT,NPTS,0)
      CALL MESSAG(ID,80,0.0,-0.8)
      CALL MESSAG(LABEL,36,0.0,-1.0)
      CALL MESSAG('FREQ = ',7,0.0,-1.2)
      CALL REALNO( FREQ,3,0.7,-1.2)
      IF(IFLAG .EQ. 1) CALL MESSAG('DMIN =',6,2.0,-1.2)
      IF(IFLAG .EQ. 1) CALL REALNO( DMIN,1,2.7,-1.2)
      CALL MESSAG('SIZEX=          X0=          NUMX=   ',32,0.0,-1.4)
      CALL REALNO( SIZEX,1,0.7,-1.4)
      CALL REALNO( X0,1,2.0,-1.4)
      CALL INTNO(NUMX,3.7,-1.4)
      CALL MESSAG('SIZEY=          Y0=          NUMY=   ',32,0.0,-1.6)
      CALL REALNO( SIZEY,1,0.7,-1.6)
      CALL REALNO( Y0,1,2.0,-1.6)
      CALL INTNO(NUMY,3.7,-1.6)
      CALL ENDPL(1)
      CALL BGNPL(2)
      CALL PHYSOR(2.0,2.0)
      CALL TITLE(' ',1,XLABEL,8,'DB ABOVE 1 MICROVOLT/METER',26,
     $  XLNG,YLNG)
      CALL INTAXS
      CALL YAXANG(0.0)
      CALL GRAF(0.,EXTIC,XMAX,EMIN,EYTIC,EMAX)
      CALL CURVE(XPLOT,Y2PLOT,NPTS,0)
      CALL DASH
      CALL CURVE(XPLOT,Y3PLOT,NPTS,0)
      CALL RESET('DASH')
      CALL STRTPT(XLNG-2.0,YLNG)
      CALL CONNPT(XLNG-0.9,YLNG)
      CALL MESSAG('          EZUMAG',16,XLNG-2.0,YLNG)
      CALL MESSAG('--------- EZPMAG',16,XLNG-2.0,YLNG-0.3)
      CALL MESSAG(ID,80,0.0,-0.8)
      CALL MESSAG(LABEL,36,0.0,-1.0)
      CALL MESSAG('FREQ = ',7,0.0,-1.2)
      CALL REALNO( FREQ,3,0.7,-1.2)
      IF(IFLAG .EQ. 1) CALL MESSAG('DMIN =',6,2.0,-1.2)
      IF(IFLAG .EQ. 1) CALL REALNO( DMIN,1,2.7,-1.2)
```

```
      CALL MESSAG('SIZEX=          X0=           NUMX=   ',32,0.0,-1.4)
      CALL REALNO( SIZEX,1,0.7,-1.4)
      CALL REALNO( X0,1,2.0,-1.4)
      CALL INTNO(NUMX,3.7,-1.4)
      CALL MESSAG('SIZEY=          Y0=           NUMY=   ',32,0.0,-1.6)
      CALL REALNO( SIZEY,1,0.7,-1.6)
      CALL REALNO( Y0,1,2.0,-1.6)
      CALL INTNO(NUMY,3.7,-1.6)
      CALL ENDPL(2)
      RETURN
      END
```

```
      SUBROUTINE CBESJY(Z,K,BJ,BY,KIND,NPRINT)
      IMPLICIT COMPLEX    (A-H,O-Z)
      REAL   DGMSUM,DG1,DG2,PI/3.14159265358979E0/,RRT,
     $         EULER/0.577215664901533E0/
C
C THIS SUBROUTINE CALCULATES BESSEL FUNCTIONS OF THE FIRST KIND(JN) AND
C OF THE SECOND KIND(YN).  N IS THE ORDER AND IS ALLOWED TO BE ANY
C POSITIVE INTEGER.
C THE ARGUMENT MUST BE DECLARED COMPLEX    IN THE CALLING ROUTINE.
C IF A REAL ARGUMENT IS DESIRED JUST SET THE IMAGINARY PART TO ZERO.
C FOR THE ARGUMENT Z=RHO*C EXP(I*PHI) THE EMPLOYED EQUATIONS ARE VALID
C AS FOLLOWS:
C      IF  0<RHO<13  THEN  PHI=ANY VALUE
C      IF RHO=13  OR  13<RHO<INFINITY  THEN  PHI=PI  OR  -PI<PHI<PI
C
C FOR RHO=0 J0 AND J1 ARE SET TO THEIR CORRECT VALUES.
C HOWEVER, Y0 AND Y1 ARE NOT CALCULATED SINCE THEY APPROACH INFINITY
C IN THE REAL AND/OR IMAGINARY PART. THEREFORE AN ERROR MESSAGE IS
C PRINTED.
C
C
C Z IS THE ARGUMENT.
C K IS THE ORDER.
C BJ IS THE BESSEL FUNCTION OF THE FIRST KIND.
C BY IS THE BESSEL FUNCTION OF THE SECOND KIND.
C KIND=1 CAUSES CALCULATION OF THE BESSEL FUNCTION OF THE FIRST KIND
C ONLY.
C ANY OTHER VALUE OF KIND CAUSES CALCULATIONS TO BE DONE FOR BESSEL
C FUNCTIONS OFF BOTH THE FIRST AND SECOND KIND.
C NPRINT=0 CAUSES NO DEBUG PRINTOUT.
C NPRINT=1 CAUSES DEBUG PRINTOUT.
C
C THE CALLING STATEMENT MUST HAVE DECLARED THE PARAMETERS CORRESPONDING
C  TO Z, BJ, AND BY AS COMPLEX    .
C
C
      IF(C ABS(Z) .NE. 0.E0) GO TO 7
      BJ=(0.0E0,0.0E0)
      IF(K .EQ. 0) BJ=(1.0E0,0.0E0)
      IF(KIND .NE. 1 .AND. K .EQ. 0) PRINT 400
  400 FORMAT(1H0,'*** Y NOT CALCULATED FOR ARGUMENT OF MAGNITUDE 0'//)
      RETURN
    7 IF(C ABS(Z) .LT. 13.E0) GO TO 10
C
C
C ASSYMPTOTIC EXPANSION
C
      RHO=8.*Z
      MU=4*K**2
      RT=C SQRT(2./(PI*Z))
      RRT=RT
      IF(RRT .LT. 0.) RT=-RT
      P=0.
C DO LOOP FOR CALCULATING P
```

```
      DO 1 N=1,30
      M=N-1
      MM=2*M
      IF(N .EQ. 1) GO TO 2
      TERM=(-1)*(MU-(2*MM-3)**2)*(MU-(2*MM-1)**2)/(MM*(MM-1)*RHO**2)*
     $TERM
      IF(NPRINT .EQ. 1) PRINT 100,TERM
  100 FORMAT(1X,'TERM=',2E30.15)
      P=P+TERM
      IF(C ABS(TERM) .GE. C ABS(TERMS) .OR. C ABS(TERM) .LE. 1.E-17) GO
     $TO 3
      TERMS=TERM
      GO TO 1
    2 TERM=1.E0
      P=TERM
      IF(NPRINT .EQ. 1) PRINT 100,TERM
      TERMS=TERM
    1 CONTINUE
    3 CONTINUE
      IF(NPRINT .EQ. 1) PRINT 200,P
  200 FORMAT(1H0,'P=',2E30.15)
      Q=0.
C DO LOOP FOR CALCULATING Q
      DO 4 N=1,30
      M=N-1
      MM=2*M
      MMM=2*M+1
      IF(N .EQ. 1) GO TO 5
      TERM=(-1)*(MU-(2*MM-1)**2)*(MU-(2*MM+1)**2)/(MMM*(MMM-1)*RHO**2)*
     $TERM
      IF(NPRINT .EQ. 1) PRINT 100,TERM
      Q=Q+TERM
      IF(C ABS(TERM) .GE. C ABS(TERMS) .OR. C ABS(TERM) .LE. 1.E-17) GO
     $TO 6
      TERMS=TERM
      GO TO 4
    5 TERM=(MU-1)/RHO
      Q=TERM
      IF(NPRINT .EQ. 1) PRINT 100,TERM
      TERMS=TERM
    4 CONTINUE
    6 CONTINUE
      IF(NPRINT .EQ. 1) PRINT 300,Q
  300 FORMAT(1H0,'Q=',2E30.15)
      BJ=RT*C COS(Z-K*PI/2.-PI/4.)*P-RT*C SIN(Z-K*PI/2.-PI/4.)*Q
      IF(KIND .EQ. 1) GO TO 8
      BY=RT*C SIN(Z-K*PI/2.-PI/4.)*P+RT*C COS(Z-K*PI/2.-PI/4.)*Q
    8 RETURN
C
C
C POWER SERIES EXPANSION
C
   10 NTERMS=35
      KFAC=1
      IF(K .LE. 1) GO TO 30
      DO 20 N=2,K
   20 KFAC=KFAC*N
```

```
   30 TERM=(Z/2.)**K/KFAC
      BJ=TERM
      IF(KIND .EQ. 1) GO TO 91
      DG1=0.
      DG2=0.
      IF(K .EQ. 0) GO TO 80
      DO 60 N=1,K
   60 DG2=DG2+1./N
   80 TSUM3=-TERM*DG2
      SUMT3=TSUM3
   91 DO 40 M=1,NTERMS
      TERM=TERM*(Z/2.)**2*(-1)/((K+M)*M)
      BJ=BJ+TERM
      IF(KIND .EQ. 1) GO TO 92
      DG1=DG1+1.E0/M
      DG2=DG2+1.E0/(M+K)
      DGMSUM=DG1+DG2
      TSUM3=-TERM*DGMSUM
      SUMT3=SUMT3+TSUM3
   92 IF(C ABS(TERM) .LE. 1.E-17) GO TO 50
   40 CONTINUE
   50 IF(KIND .EQ. 1) GO TO 93
      TERM3=SUMT3/PI
      TERM1=(2./PI)*BJ*(EULER+C LOG(Z/2.))
      SUMT2=(0.,0.)
      IF(K .EQ. 0) GO TO 120
      KM1FAC=KFAC/K
      TSUM2=KM1FAC*(Z/2.)**(-K)
      SUMT2=TSUM2
      IF(K .EQ. 1) GO TO 120
      KM1=K-1
      DO 130 M=1,KM1
      KMM=K-M
      TSUM2=TSUM2/(KMM*M)*(Z/2.)**2
  130 SUMT2=SUMT2+TSUM2
  120 TERM2=-SUMT2/PI
      BY=TERM1+TERM2+TERM3
   93 RETURN
      END
```

```
      SUBROUTINE CLIN EQ (A,B,X,IROW,Q,N,NDIM,IFLAG,ERR)
C
C   CLIN EQ USES L-U DECOMPOSITION TO
C   FIND THE TRIANGULAR MATRICES L, U
C   SUCH THAT  L * U = A.  L AND U ARE
C   STORED IN A.  THIS FORM IS USED WITH
C   BACK-SUBSTITUTION TO FIND THE SOLN
C   X OF   A * X = L * U * X = B.
C   N IS THE NUMBER OF EQUATIONS AND
C   N DIM IS THE DIMENSION OF ALL ARRAYS
C   IN THE PARAMETER LIST.
C
C   IF IFLAG = 0, L, U, AND X ARE
C   COMPUTED.
C   IF IFLAG IS NON-ZERO, IT IS ASSUMED
C   THAT L AND U HAVE BEEN COMPUTED IN
C   A PREVIOUS CALL AND ARE STILL STORED
C   IN A.  THUS ONLY X IS COMPUTED.
C   ERR  IS THE ESTIMATED RELATIVE
C   ERROR OF THE SOLUTION VECTOR.
C
      COMPLEX     A, B, X, T
      REAL   ERR
      DIMENSION A(NDIM,NDIM),B(NDIM),X(NDIM)
      DIMENSION  IROW(NDIM),Q(NDIM)
      DATA  EPS /1.0E-15/
C
C
      IF (N.GT.NDIM) GO TO 900
      IF (IFLAG.NE.0)  GO TO 600
      DO 050  I = 1,N
      Q(I) = 0.0
      DO 040  J = 1,N
      QQ = C ABS (A(I,J))
  040 IF (Q(I).LT.QQ)  Q(I) = QQ
      IF (Q(I).EQ.0.0)  GO TO 901
  050 CONTINUE
      ERR = EPS
      PPIV = 0.0
      DO 100  I = 1,N
  100 IROW(I) = I
C
      DO 500  L = 1,N
      PIVOT = 0.0
      K = L - 1
      DO 240  I = L,N
      IF (K.LT.1)  GO TO 230
      DO 220  J = 1,K
  220 A(I,L) = A(I,L) - A(J,L) * A(I,J)
  230 F = C ABS (A(I,L)) / Q(I)
      IF (PIVOT.GT.F)  GO TO 240
      PIVOT = F
      NPIVOT = I
  240 CONTINUE
```

```
      IF (PIVOT.EQ.0.0)  GO TO 901
      IF (PPIV.LE.PIVOT)  GO TO 250
      ERR = ERR * PPIV / PIVOT
      IF (ERR.GE.1.0)  GO TO 901
  250 PPIV = PIVOT
      IF (NPIVOT.EQ.L)  GO TO 280
      Q(NPIVOT) = Q(L)
      J = IROW(L)
      IROW(L) = IROW(NPIVOT)
      IROW(NPIVOT) = J
      DO 260  I = 1,N
      T = A(L,I)
      A(L,I) = A(NPIVOT,I)
      A(NPIVOT,I) = T
  260 CONTINUE
  280 IF (L.EQ.N)  GO TO 500
      T = (1.0E0,0.0E0) / A(L,L)
      K = L + 1
      M = L - 1
      DO 450  I = K,N
      IF (M.LT.1)  GO TO 400
      DO 350  J = 1,M
  350 A(L,I) = A(L,I) - A(L,J) * A(J,I)
  400 A(L,I) = T * A(L,I)
  450 CONTINUE
  500 CONTINUE
      IF (ERR.GT.1.0E-5)   PRINT 998, ERR
C
C
  600 DO 620  I = 2,N
  620 X(I) = (0.0E0,0.0E0)
      J = IROW(1)
      X(1) = B(J) / A(1,1)
      DO 700  I = 2,N
      J = IROW(I)
      K = I - 1
      DO 650  L = 1,K
  650 X(I) = X(I) + A(I,L) * X(L)
      X(I) = (B(J) - X(I)) / A(I,I)
  700 CONTINUE
      K = N - 1
      DO 800  I = 1,K
      J = N - I
      M = J + 1
      DO 800  L = M,N
      X(J) = X(J) - X(L) * A(J,L)
  800 CONTINUE
      RETURN
C
  900 PRINT 999
      ERR = 1.0
      RETURN
  901 PRINT 997
      ERR = 1.0
      RETURN
  997 FORMAT ('1ERROR IN CLIN EQ, MATRIX IS SINGULAR')
  998 FORMAT (' CAUTION-',
```

```
     $ ' CLIN EQ HAS DECOMPOSED AN ILL-CONDITIONED MATRIX.',/,
     $ ' RESULTS WILL HAVE RELATIVE ERROR =',E11.2)
 999 FORMAT ('1ERROR IN CLIN EQ, MATRIX SIZE GREATER THAN NDIM')
      END
```

```
      FUNCTION C ANG(ARG)
      IMPLICIT REAL   (A-H,O-Z)
      COMPLEX    ARG,MINUSI/(0.0E0,-1.0E0)/
      ARGR=ARG
      ARGI=MINUSI*ARG
      C ANG= ATAN2(ARGI,ARGR)
      IF(ARGI .LT. 0.) C ANG=C ANG+6.2831853072E00
      RETURN
      END
```

```
      COMPLEX FUNCTION CAPA(SP,RHO)
      IMPLICIT COMPLEX   (A-H,O-Z)
      COMPLEX    IM/(0.E0,1.E0)/,J1,J2
      COMPLEX KS0
      REAL KA,RHO
      COMMON/ONE/H12,H22,J1,J2,S0,ARG0,KA,KS0
      DEFINE CAPG1(ARG) =  SQRT(ARG/(6371.0E0* SIN(ARG/6371.0E0)))
      ARGP = KA*SP
      TERM1 = (0.0E0,0.785398163397448E0)*((SP/S0)**2-1.0E0)
      TERM2 = 2.0E0*ARG0*(1.0E0-.25E0*ARGP**2)
      IF(RHO .EQ. 0.0) THEN
                 CAPA = (SP/S0)**4+TERM1*(TERM2*H12+ARGP**2*H22)
             ELSE
                 COFAMN = TERM1*(TERM2*J1+ARGP**2*J2)
                 ARGU = KS0*RHO
                 CALL CBESJY(ARGU,0,BJ,BY,0)
                 H02 = BJ-IM*BY
                 CAPA = COFAMN*H02*CAPG1(RHO)
      END IF
      RETURN
      END
```

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