Jan Carlsson

A Computer Code for Calculation of the Penetration of Electromagnetic Fields through Slots

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Abstract

A computer code for calculation of the penetration of electromagnetic fields through slots

This document describes the idea behind and the use of the PC computer code CORRSLOT 1.0. The computer code is designed for calculation of the penetration of electromagnetic fields through a slot in an infinitely large and perfectly conducting ground plane. The slot cross section can, by the user, be defined as a number of subsequent rectangular sections. This capability makes it possible to perform calculations on corrugated slots.

The exciting field is a plane wave with either TE or TM polarisation and an arbitrary incidence angle. The theory for the calculation of the field penetration is based on an integral formulation and the numerical results are obtained by the use of the method of moments. Calculated quantities are the electric field distribution in the slot, the attenuation and the far field radiation pattern.

Key words: Corrugated slot, Method of moments, Numerical simulation, Slot

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Swedish National Testing and Research Institute
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Postal address:
Box 857, S-501 15 BORÅS, Sweden
Telephone +46 33 16 50 00
Telex 36252 Testing S
Telefax +46 33 13 55 02

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Summary

Slots are important since they offer a leakage path for electromagnetic energy from one region into another. In EMC-design it is often very helpful to be able to quantify the amount of leakage in order to compare with the contributions from other coupling paths. In many cases, however, it is obvious, simply by looking at the system, that the most important coupling path is a slot. In such a system it is necessary to have the knowledge of the effects of the slot in order to be able to determine the interaction between, e.g., the outer environment and the electronics placed behind the slot.

In order to determine the amount of leakage through a slot, it is necessary to determine the field distribution in the slot. This can be done by dividing the problem into different regions, by the aid of the equivalence principle, where the field expressions, i.e. Green's functions, can be determined. Then, by matching the fields at the boundaries between the different regions, the original problem can be solved. The matching has to be performed in such a way that the boundary conditions of continuos tangential field components are satisfied. This procedure will lead to a set of integral equations for the unknown field distributions at the slot faces (at the boundaries between different regions).

To obtain a numerical solution of the set of integral equations, the method of moments is used. The method of moments is a method to transform an operator equation to a matrix equation that can be solved by an ordinary matrix inversion. Since matrix inversion is easily performed on a computer the method of moments is well suited for computer applications.

When the field distribution in the slot is calculated other quantities can be computed, such as the radiation pattern and the attenuation.

A computer code named CORRSLOT was developed by following the procedure just discussed. This code is the subject of this document and in the following descriptions are given regarding the capabilities, installation and how to use the program. The last chapter of this document is devoted to a number of sample runs that are used for highlighting the use of the code.

The code is available through the author.

1 Introduction

CORRSLOT is a computer code usable on a PC capable of calculating the equivalent magnetic current in an infinitely long slot. The slot can either be placed in a ground plane of finite thickness or zero thickness. In the case of zero thickness multiple slots can be analysed by defining up to three conducting bars running parallel to the slot axis and placed at arbitrary positions. Corrugated slots can also be analysed by defining the cross section of the slot as a number of subsequent rectangular sections. The geometries that can be analysed by the code are shown in figure 1.

The calculations are based on the moment method and collocation (point matching) is used for TE-polarisation and Galerkin's method with triangle functions for TM-polarisation. Besides the equivalent magnetic current in the slot, the radiated field (scattered) from the slot and the attenuation in the slot are calculated. The excitation of the slot is an incident plane wave with polarisation TE or TM and an arbitrary incidence angle.

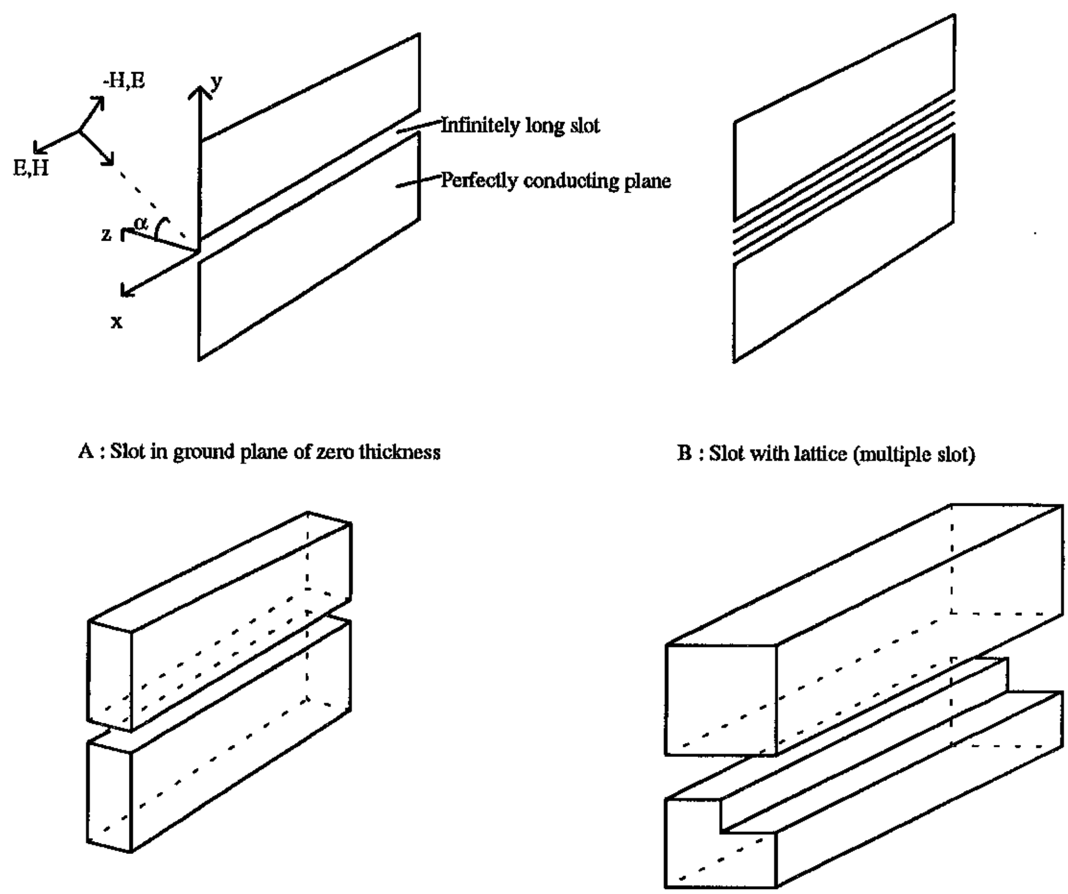

Figure 1. Geometries for the problems treated by the program CORRSLOT.

Referring to figure 1 the polarisation of the exciting field is defined as TM when the electric field vector is parallel with the slot axis (the x-axis) and as TE when the magnetic field vector is parallel to the slot axis.

The incidence angle of the exciting field is defined as the angle between the direction of propagation and the z-axis, i.e. the α-angle in figure 1.

The exciting field is a plane wave with a magnetic field amplitude of unity and thus an electric field amplitude of 377 [V/m].

2 Hardware requirement

IBM compatible computer running under DOS operating system with a minimum of 640 kbyte of RAM memory. A math coprocessor is necessary and additional RAM memory is highly recommended to speed computations.

The program is supporting a mouse but the mouse is not necessary for running the program. If a mouse is to be used the mouse driver should be activated before the program is started.

The computer code is written in Turbo Pascal 6.0 and Turbo Vision by Borland and Huge Virtual Array & Numerical Analysis Toolbox by Quinn-Curtis are used.

The code allocates memory for the matrices used in the computations. First conventional memory is used, after that extended memory (up to 16 MB) and last hard disk memory is used. The memory requirement depends on the number of basis functions, i.e. the number of functions in the series for the unknowns, wanted by the user.

If the number of basis functions is denoted by N the memory used for data storage is:

$16[N(3N+3)+181]$ Bytes

2.1 Installation

The program can be run from the distribution diskette but it is recommended that the program is installed in its own directory on a hard disk. If the hard disk drive is C and the directory where the program is to be placed is SLOTPROG, the procedure is as follows :

- Make sure that the current drive is C:\

- Make directory SLOTPROG
  C:\> md SLOTPROG

- Change current directory to SLOTPROG
  C:\> cd SLOTPROG

- Copy all the files from the distribution diskette to the current directory
  Insert the distribution diskette in drive A
  C:\SLOTPROG> copy A:*.*

After installation the program CORRSLOT can be run from the directory SLOTPROG by simply writing CORRSLOT at the prompt.

On the distribution diskette a PIF file, CORRSLOT.PIF, and an icon file, CORRSLOT.ICO, are also supplied. These files can be used if the program is to be run from Windows. For details of how to run a DOS program under Windows please see the Windows manuals. However, the supplied PIF file is recommended.

3 Theory of operation

The derivation of the integral equation for the slot and how the equation is solved by the method of moments is in detail described in a CTH-report which is to be published during 1993. The title of this report will be "Two-dimensional corrugated slot in a ground plane treated with the method of moments".

Before the program is started the mouse driver is recommended to be started, although it is possible to run the program without a mouse.

When the program is started an empty screen with a menu bar at the top and a status line at the bottom of the screen will appear. In the status line the short-cut command for quitting the program is given. This information remains as long as the program is running.

By moving the mouse pointer to one of the items in the menu bar and clicking the mouse button or by pressing the Alt-key simultaneously with one of the highlighted characters, a pull down menu will appear. By choosing one of the alternatives in the pull down menu the command is executed or a dialog box will appear.

The various pull down menus and the dialog boxes are described one by one below.

3.1 File - menu

Under the file menu three alternatives are given: Data to save, Save data and Exit.

By choosing the command Data to save a dialog box will appear. In the dialog box it is possible to choose what type of data to save and the file name under which the data is saved. The data types are : Equivalent magnetic currents or radiation pattern. The default file name is : Temp.dat (stored in current directory).

The equivalent magnetic current is defined as the cross product between the electric field in the slot and the normal vector to the slot. Thus, the equivalent magnetic current is equal to the tangential electric field in the slot. This means that the equivalent magnetic current represents the x-directed electric field in the slot for the TM-case and the y-directed electric field for the TE-case.

For pattern type of data, the saved data are the angle θ (see figure 2) and the normalised magnetic or electric field in decibels in the far field region. For TM-polarisation the x-directed electric field is saved and for TE the x-directed magnetic field. Normalisation is performed in such a way that the radiated field will be divided with the field strength of the excitation field. In this way the radiated field pattern is a picture of the attenuation for different directions in the far field region.

In the far field region the electric and the magnetic fields are orthogonal to each other and the ratio is equal to the free space intrinsic impedance, 377 Ω. Thus, the magnetic field pattern is also a picture of the electric field and vice versa.

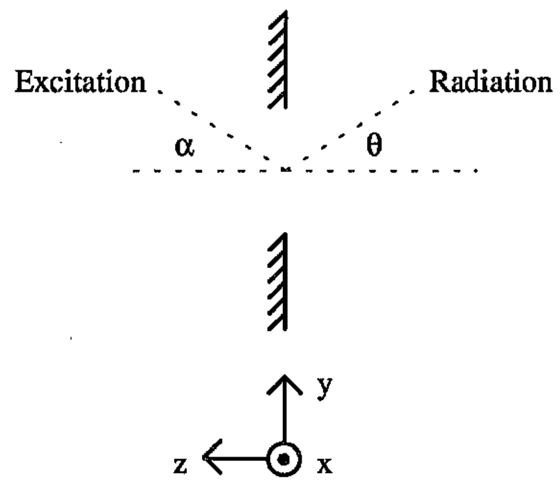

Figure 2. Definition of angle α and θ.

The command Save data will have the effect of saving calculated data in an ASCII-file, i.e if a calculation was performed. The type of data and the file name are defined under the command Data to save.

The command Exit will have the effect of leaving the program and returning the control to DOS. A dialog box prompting for confirmation will appear before quitting is allowed.

3.2 Geometry - menu

Under the geometry menu parameters describing the slot cross-section, i.e. slot width, ground plane thickness, lattice and corrugations are defined.

When the command Define slot is chosen a dialog box will appear. In the dialog box it is possible to define slot dimensions. The choices are : Slot width, Ground plane thickness and relative permittivity (relative to free space). The permittivity is only in effect when the ground plane thickness is not equal to zero.

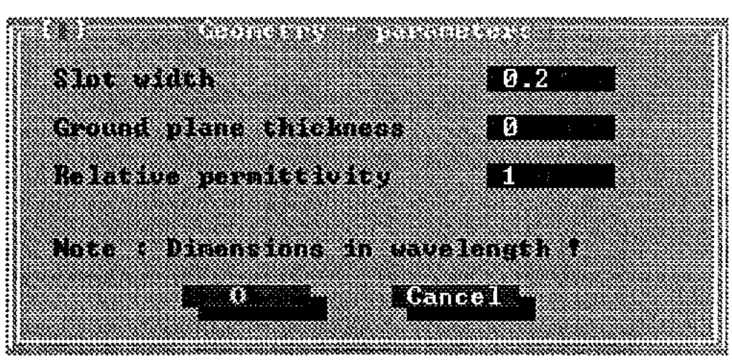

Figure 3. The geometry parameter dialog box.

The dimension of the slot should be given in terms of the free space wavelength (with this convention it is not necessary to define the frequency of the exciting field).

By choosing the command Define corrugations the following dialog box will appear :

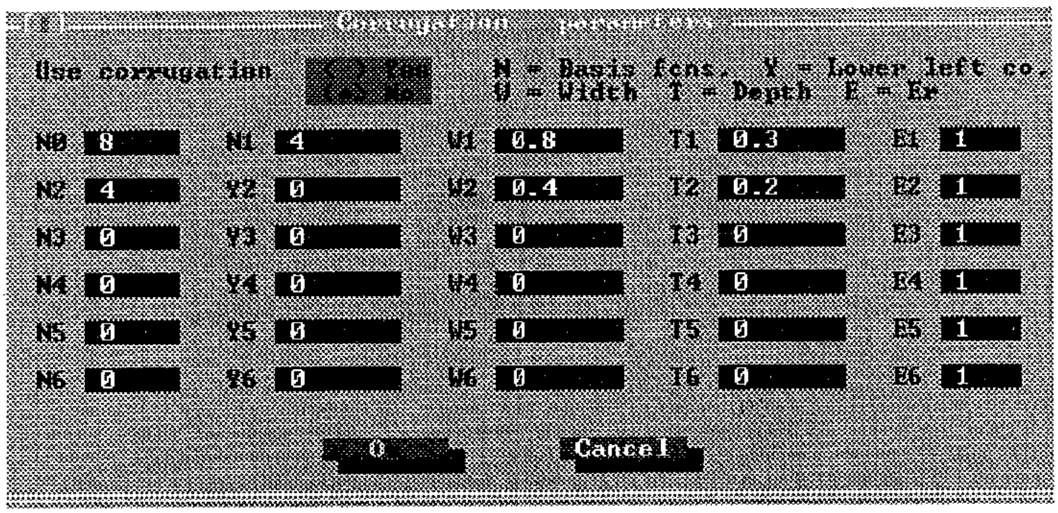

Figure 4. The corrugation parameter dialog box.

In the dialog box it is possible to define up to six coupled rectangular regions that together defines the corrugations.

The parameters are defined as (see figure 5) :

Nk : Number of basis functions at the boundary between region k and k+1.
N0 = the magnetic current at the extreme left boundary.

Yk : Y-co-ordinate for the lower left corner of region k.
Y1 = 0.

Wk : Width of region k.

Tk : Depth of region k.

Ek : Relative permittivity in region k (relative to free space).

Note : All dimensions should be given in terms of the free space wavelength.

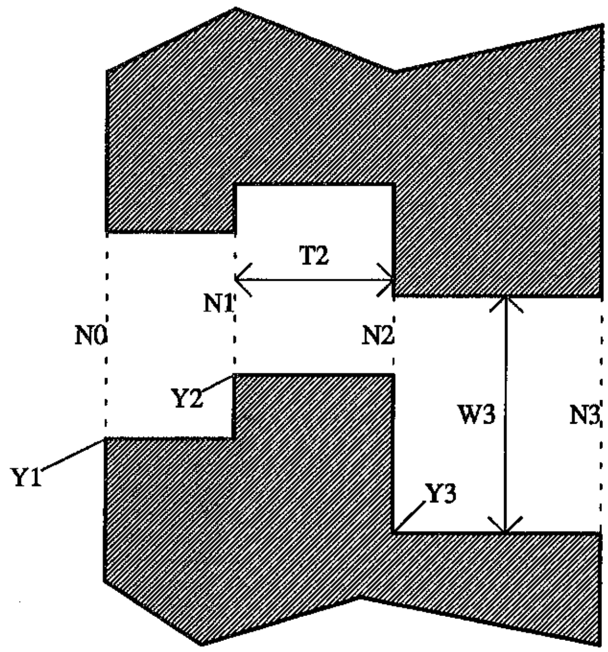

Figure 5. Example of corrugated slot.

By choosing the command Visualize corrugations a picture showing the cross section is drawn (similar to the picture shown in figure 5).

The lattice option makes it possible to perform calculations not only for a single slot but also for a multiple slot, i.e. a lattice.

By choosing Define lattice a dialog box for definition of the lattice is shown.

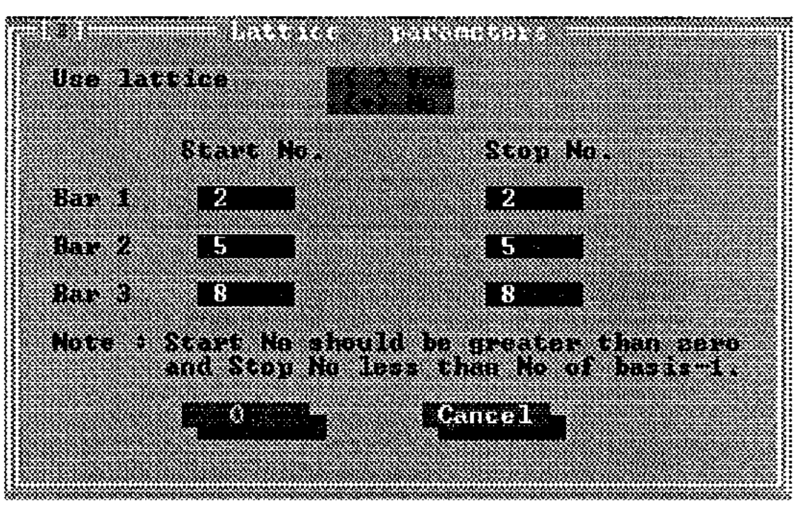

Figure 6. The lattice define parameters dialog box.

The first choice in the dialog box is whether the lattice definition should be used in the calculations or not. If "No" is chosen (default value) calculations are performed for a single slot regardless of the other lattice parameters.

The lattice consists of three bars with arbitrary widths and they can be placed at arbitrary positions in the slot. The width and position of a bar are defined by a start number and a stop number. If only one bar is wanted the three bars should have the same start and stop numbers, in this way the three bars will overlap each other.

How the start and stop numbers should be chosen for a specific bar width and position is most easily understood if figure 7 is considered.

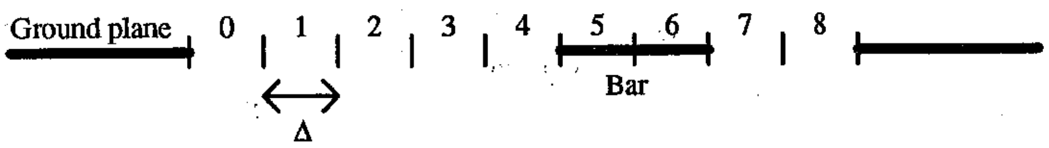

Figure 7. Slot with one bar. Number of basis functions is nine.

Referring to figure 7 the slot is divided into small subsections each with a length of Δ. The number of subsections, Δ, is equal to the number of basis functions, which in turn is defined in the excitation parameter dialog box, see ch. 3.3. The subsections are numbered from zero to the number of basis functions minus one. The start and stop number of the bar are defined as the numbers of the subsections, Δ, occupying the wanted location of the bar. Again, referring to figure 7, the bar in the figure will have the start number equal to 5 and the stop number equal to 6.

It should be noted that the location as well as the width of a bar depend on the number of basis functions.

By choosing <u>Visualize lattice</u> a plot similar to the one shown in figure 7 is drawn.

3.3 Excitation - menu

By choosing Define type under the excitation menu the following parameter dialog box will appear :

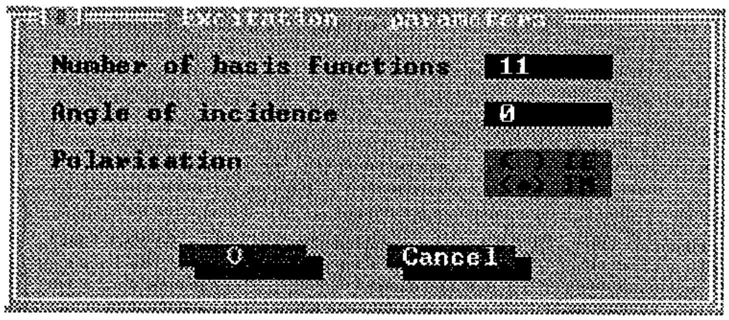

Figure 8. Excitation parameter dialog box.

The number of basis functions is an integer greater or equal to three. The memory allocated by the program is proportional to the number of basis functions, N, raised to two (see chapter 2 above) and the time needed for computation is roughly proportional to N raised to three. Thus, a doubling of the number of basis functions will take four times more of memory and the time for computation will be roughly eight times longer. The accuracy of the equivalent magnetic current is dependent on the number of basis functions and therefore the number should be sufficiently large for a certain accuracy.

It is recommended that the number of basis functions is doubled until the amplitude of the equivalent magnetic current in the slot has become steady. Otherwise, as a rule of thumb, the number of basis functions can be set to about twenty per wavelength.

The angle of incidence α, as defined in figure 1 and 2, should be input in degrees. Valid range is from -90 to +90 degrees.

The polarisation of the exciting incident field is defined as either TE or TM. By TM it is meant that the electric field vector is parallel with the slot axis, i.e. the electric field vector is x-directed in figure 1. In this case the equivalent magnetic current in the slot is directed along the negative y-axis.

For TM-polarisation the exciting magnetic field vector is directed along the x-axis and the equivalent magnetic current in the slot is x-directed.

3.4 Run - menu

The run menu contains one choice. By selecting Run in the menu the user is prompted with a dialog box asking for confirmation. In the dialog box the type of simulation is also given. Four different types of simulations are possible (depends on the geometry etc.), these are :

- Zero thickness : Geometry of figure 1 A
- Lattice : Geometry of figure 1B
- Finite thickness : Geometry of figure 1C
- Corrugated slot : Geometry of figure 1D

If the user answers "Yes" on the question if the computation shall be started, the computation will be started and a "wait" window will be shown. If, on the other hand, the user answers "No" the control will be returned to the main level and the user is able to modify parameters.

When the computation is ready the "wait" window will disappear and the computer will sound to call for attention.

3.5 Plot - menu

In the plot menu two choices are given, these are : Plot and Plot file.

If Plot is chosen a dialog box prompting for the type of data to plot is shown, the choices are Current and Pattern. When one of the two is selected the most recent calculated data are plotted. The plotting routine is working as described below.

If Plot file in the plot menu is chosen a dialog box prompting for the filename of the data which are about to be plotted will appear. The data should be arranged in the same way as the data saved by the program CORRSLOT, i.e. five real-valued numbers at each row separated by a space (see chapter 4 below). This means that the data which are to be plotted do not necessarily have to be generated by the program CORRSLOT. However, the plotting routine is assuming that the data were generated by CORRSLOT and consequently the plot titles are adopted to that.

When "Ok" in the dialog box is chosen the plotting routine is started. However, two possible errors may appear, i.e. the plotting routine cannot be found and available memory is not enough.

The first error appears if the plotting routine, CORRPLOT.EXE, is not located in the current directory. The low-memory error appears if, for instance, a network driver is running simultaneously.

When the plotting routine is started successfully a menu screen will appear. In the menu screen three different choices are available, these are : Define what to plot, Plot and Quit.

By choosing the command "Define what to plot" a new menu screen will appear. In this menu four choices for what to plot are available, these are : Amplitude, Phase, Real-part and Imaginary-part. The parameter that is about to be plotted is chosen by simply pressing the key that corresponds to the first letter in the word, i.e. A, P, R or I. Pressing any other key will have the effect of leaving this menu and returning to the main menu. In the main menu the current choice is shown below the command choices.

When "Plot" in the main menu is chosen, a plot of the selected parameter will be drawn. The plot is scaled automatically in such a way that the maximum parameter value will correspond to the top of the screen and the minimum value to the bottom of the screen. The x-axis is scaled in the same way. Pressing any key but the "M" key will have the effect of returning the control to the main menu.

By pressing the "M" key, when the plot is visible, a marker will appear. The marker can be moved around the screen by pressing the number keys (2, 4, 6 and 8 for down, left, right and up) or, for some keyboards, the arrow keys when Num Lock is on. The speed of the marker, i.e. how many pixels the marker will move for each press on one of the arrow keys, can be adjusted by pressing the "-" and the "+" key. Pressing the "+" key will increase the speed and "-" will decrease the speed. By pressing the "Q" key the control is returned to the main menu.

When the "Q" key is pressed at the main menu level, the control is returned to the program CORRSLOT.

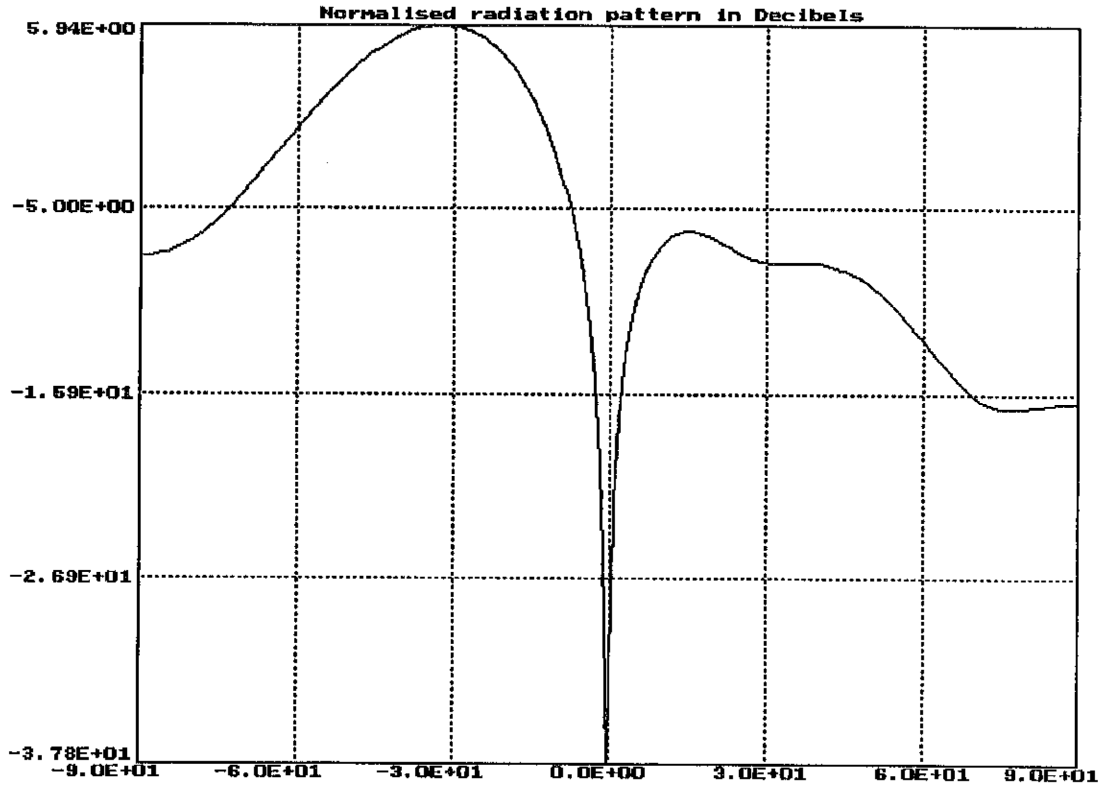

Figure 9. Sample plot of radiation pattern calculated with CORRSLOT and drawn by the plotting routine.

3.6 Status - menu

Only one choice is given under the status menu and that is Show status.

If Show status is chosen a screen showing the current status of the code is shown, one example is shown in figure 10 below.

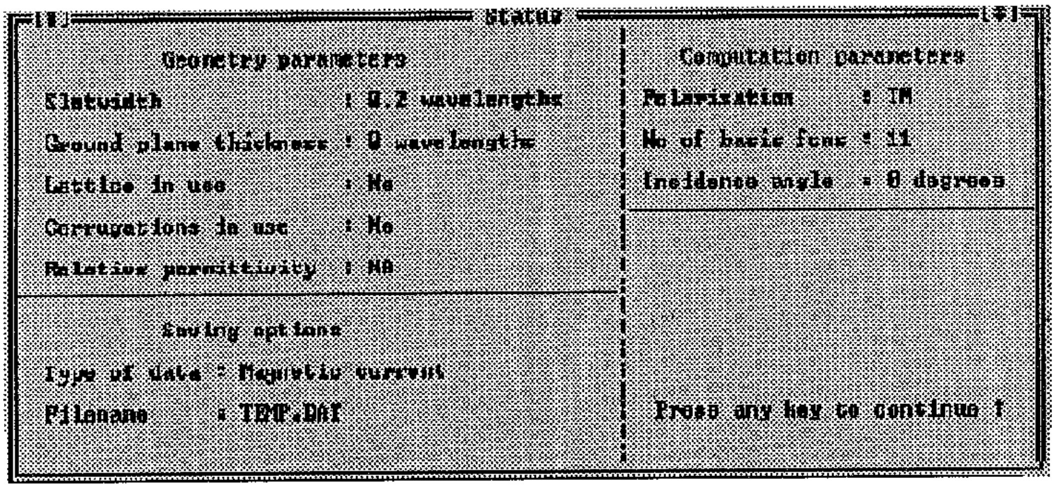

Figure 10. Example of status screen.

3.7 Help - menu

In the help pull down menu two choices are available, these are : Info and Advise. By selecting one of the choices a window containing information about the program or computation advise is shown. The window can be moved around on the screen by placing the mouse pointer at the top border and dragging the window. The window is closed by clicking with the mouse at the small box at the top left corner in the window. The most recently opened window can also be closed by Alt-F3.

4 Output

The attenuation in the slot is presented in a window after computation. The window can be moved around on the screen by placing the mouse pointer at the top border and dragging the window. This is helpful when several subsequent computations are performed since the result window will appear at the same location after each run. The window can be closed either by clicking the mouse at the box in the top left corner or by pressing Alt-F3.

The presented attenuation is defined as the ratio of the total radiated power from the slot in the half space $z<0$ to the incident power at the slot.

It should be noted that the attenuation is not saved in a file.

Depending on the choice of current or pattern type of data (file menu - data to save), the saved file will contain current or radiated field parameters. The various parameters will be saved in a table form as shown below.

<u>Current type of data</u>

Y-co-ordinate in the slot_Amplitude_Phase_Real part_Imaginary part

Where the "_" character is denoting a space.

<u>Pattern type of data</u>

θ-angle_Normalised field amplitude in decibels_0_0_0

Where the "_" character is denoting a space.

5 Sample runs

In this section a few sample runs are presented in order to show how the code is used.

5.1 Simple slot in a thick ground plane

The task of this example is to determine the equivalent magnetic currents (tangential electric fields) in the slot shown in figure 11 at z=0 and z =-T. The excitation should be a normally incidence plane wave with TM-polarisation .

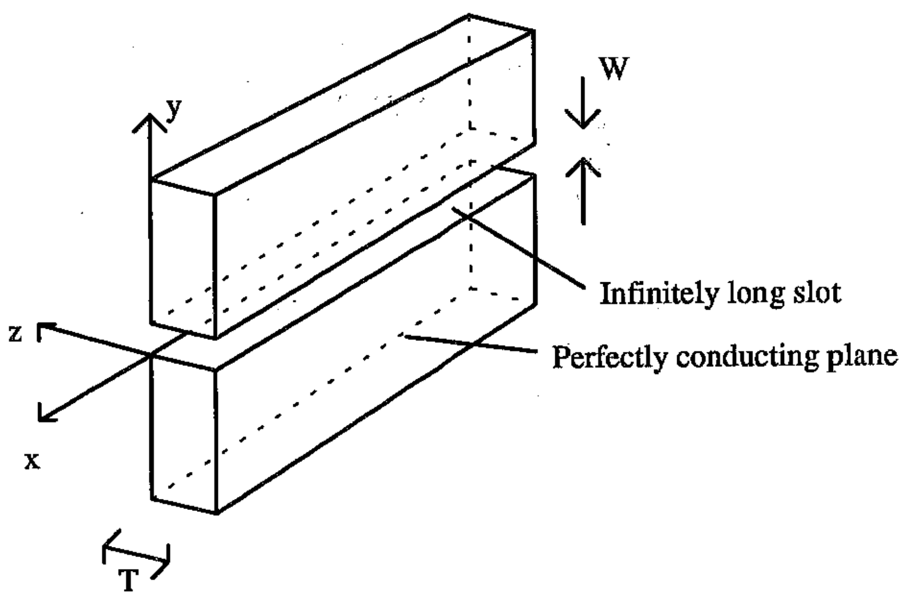

Figure 11. Geometry for the problem.

The dimensions of the slot are : $W = 0{,}2\ \lambda$ (the width)
$T = 0{,}01\lambda$ (the ground plane thickness)

By using the program CORRSLOT the procedure to solve the problem would step by step be as follows.

A. Define the geometry for the slot

- Choose Geometry - Define slot to bring forward the geometry parameters dialog box.

- Input the parameter values in the corresponding positions in the dialog box. The position is chosen by clicking the mouse pointer in the input field or by repetitively pressing the Tab-key.

- Choose OK or press Enter when all parameters are correctly input.
- Before leaving the parameter dialog box it should look like the one shown in figure 12.

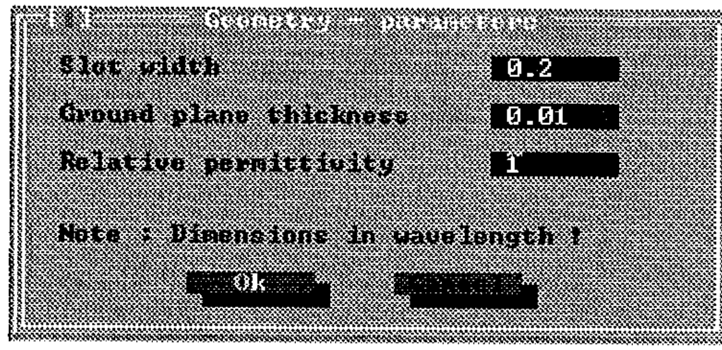

Figure 12. Geometry parameters dialog box for the problem in figure 11.

Note that the relative permittivity is left as unity because there is no dielectric in the slot of this problem.

B. Define the excitation type

- Choose Excitation - Define type to bring forward the excitation dialog box.
- Change the number of basis functions to 10.
- Leave the incidence angle at zero degrees, that is because we should have a normally incidence on the slot.
- Choose TM-polarisation by clicking the mouse pointer next to TM (inside the brackets) or by pressing the Tab-key to highlight the row "Polarisation" and use the arrow keys to toggle between TE and TM.
- When all parameters are correct, choose OK or press Enter. (By choosing Cancel the changes made are not executed, this is valid for all dialog boxes).

C. Perform calculation

- Choose Run - Run to bring forward the run confirmation dialog box.
- Before pressing Yes be sure that the simulation type is "Finite thickness".

  If it is not choose No and do as follows :

  - If the simulation type was "Lattice" choose the Geometry - Define lattice and choose Use lattice : No.
  - If the simulation type was "Corrugated slot" choose Geometry - Define corrugations and choose Use corrugations : No.
- When the simulation type is "Finite thickness" press Yes (just pressing Enter will not do the job this time).

During calculations a wait window is shown and when the calculations are ready the computer will sound and a window giving the attenuation in the slot is shown. For this example the attenuation should be 8,70 dB.

D. Plot the equivalent magnetic currents (tangential electric fields)

- Choose Plot - Plot to bring forward the plot dialog box.
- Choose Current and press OK.
- At the main menu in the plotting routine press P to plot the amplitude of the equivalent magnetic currents. A curve like the one shown in figure 13 should be shown. In the plot the solid line, MA, represents the equivalent magnetic current in the slot at z=0 and the dotted line, MB, represents the current at z=-T.
- By pressing M when the plot is shown a marker will appear. The marker is moved by pressing the arrow keys, when Num lock is on. The speed of the marker can be increased by repetitively pressing the "+" key and decreased by pressing the "-" key.

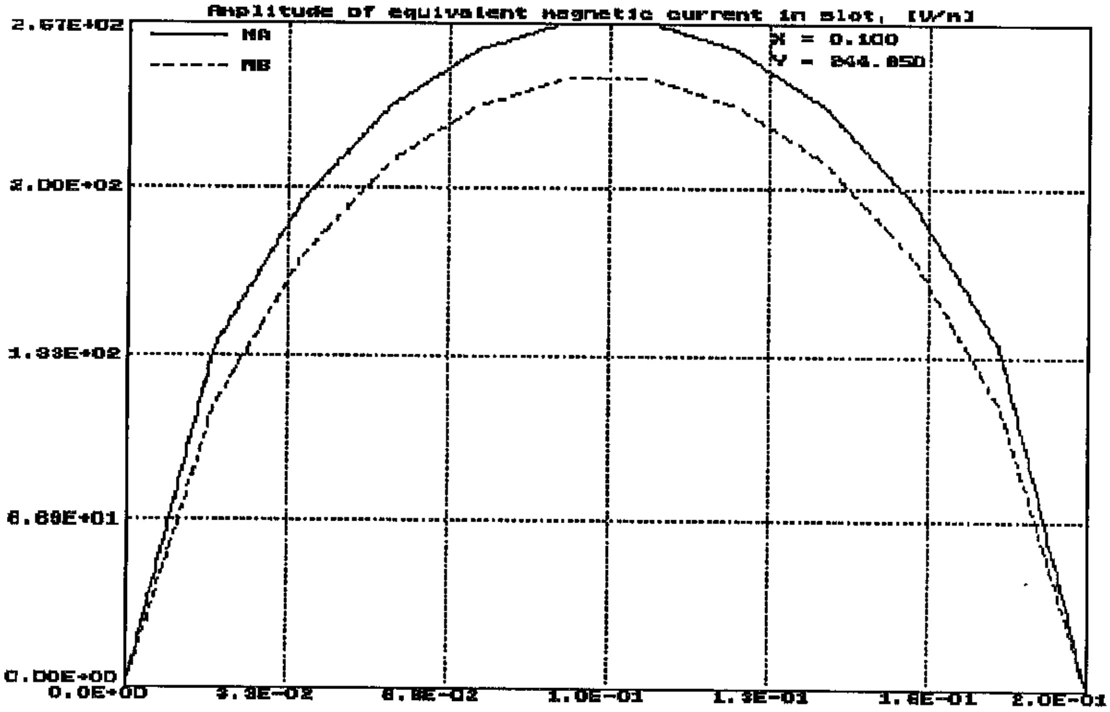

Figure 13. The equivalent magnetic currents at z=0 and z=-T for the problem shown in figure 11. The marker is placed at the top of MB.

In figure 13 it is seen that the equivalent magnetic currents, which are equal to the x-directed electric fields in the slot, are equal to zero at y=0 and y=W (=0,2λ). This should be expected because of the boundary condition for the tangential electric field at the perfectly conducting ground plane which is that of vanishing field. It is also seen that the field amplitude at z=-T is lower than the amplitude at z=0. This is due to the attenuation of the wave on its way from z=0 through the slot to z=-T.

5.2 Multiple slot in a thin ground plane

In this example the radiation pattern from a multiple slot in a thin ground plane will be determined. The multiple slot is defined by using the lattice option which is available in CORRSLOT.

The dimensions for the multiple slot are shown in figure 14.

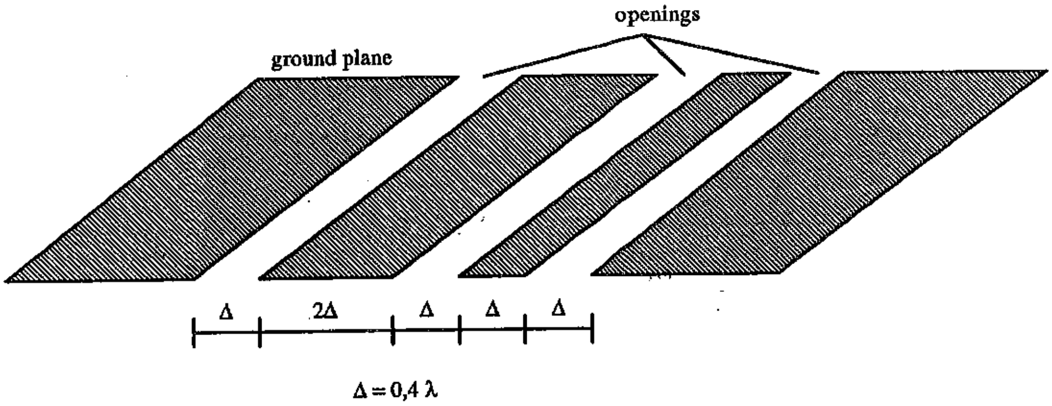

Figure 14. Three slots in a thin ground plane.

The procedure for determination of the radiation pattern for the case of TM-polarisation will be as follows :

A. Define the geometry for the slots

- Choose Geometry - Define slot to bring forward the geometry parameters dialog box.

- Input 2,4 in the box for the slot width. Note : the width should be set to the distance between the extreme left and the extreme right of all slots (=6 × Δ = 2,4λ).

  The choices in the other two boxes will have no effect on the computation why you can leave them as they are.

- When the width is correct choose OK or press Enter.

- Choose Geometry - Define lattice to bring forward the lattice parameters dialog box.

- Choose Use lattice by clicking in the brackets at Yes.

- If we suppose that the number of basis functions is set to 60 the start and stop numbers for the bars will be (remember that the bars define the ground planes in between the slots) :

Bar 1 :	Start : 11	Stop : 30
Bar 2 :	Start : 41	Stop : 50
Bar 3 :	Start : 41	Stop : 50

Note : since we only need two bars to define the geometry shown in figure 14, bar 3 should be set to the same as either bar 1 or bar 3 (by this they will overlap each other).

- When all parameters are correct choose OK or press Enter.

- Choose Geometry - Visualize lattice to show the cross section of the multiple slot. By doing this you will probably get an error message ! This is because the number of basis functions was supposed to be set to 60 when we defined the lattice bars but the number of basis functions set in the Excitation - Define type dialog box is less (less than 51).

When the next step is performed you can return to Geometry - Visualize lattice to show the geometry.

B. Define the excitation type

- Choose Excitation - Define type to bring forward the excitation dialog box.

- Change the number of basis functions to 60.

- Leave the incidence angle at zero degrees.

- Choose TM-polarisation.

- When all parameters are correct, choose OK or press Enter.

C. Perform calculation

- Choose Run - Run and press Yes.

D. Plot the radiation pattern

- Choose Plot - Plot to bring forward the plot dialog box.

- Choose Pattern and press OK.

If everything is correct a figure like the one shown in figure 15 should be visible on the screen.

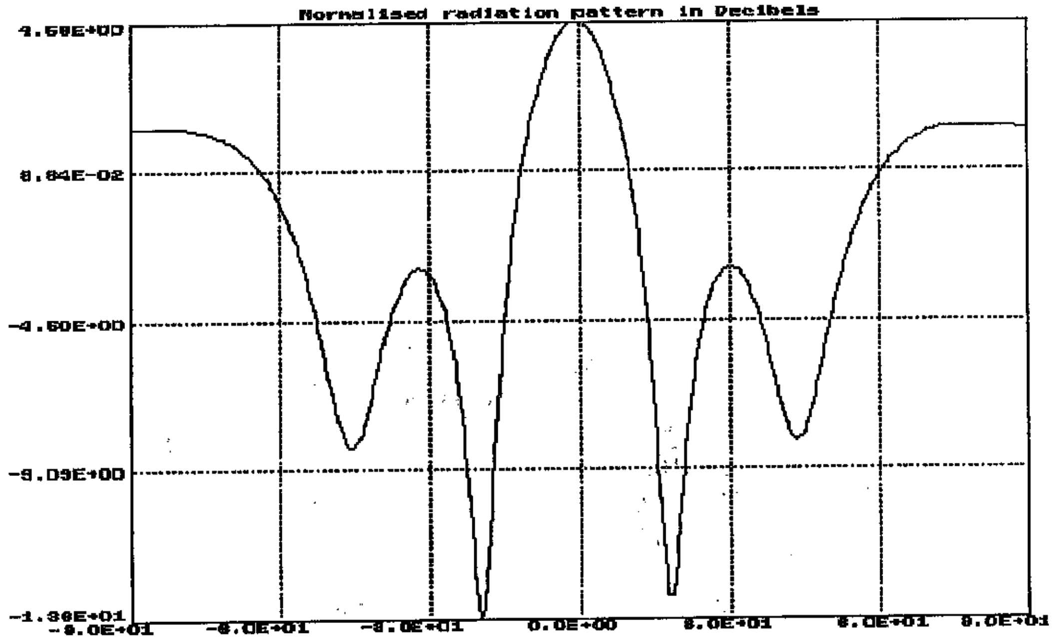

Figure 15. Radiation pattern for the geometry in figure 14, i.e. $|E_x^{tot}|$.

5.3 Corrugated slot

In this example it will be shown how the attenuation in a narrow slot can be increased by the use of a corrugation.

For the TE-case the attenuation is practically equal to zero and almost independent of the width of the slot. Thus, some other method (other than decreasing the width) to increase the attenuation must be used. The use of a corrugation is one such method and it is the technique that will be demonstrated in this example.

Suppose that some material is milled off the two ground planes in figure 11 in such a way that a groove is created in each plane, i.e. a corrugation. The cross section of the slot will then look like the one shown in figure 16.

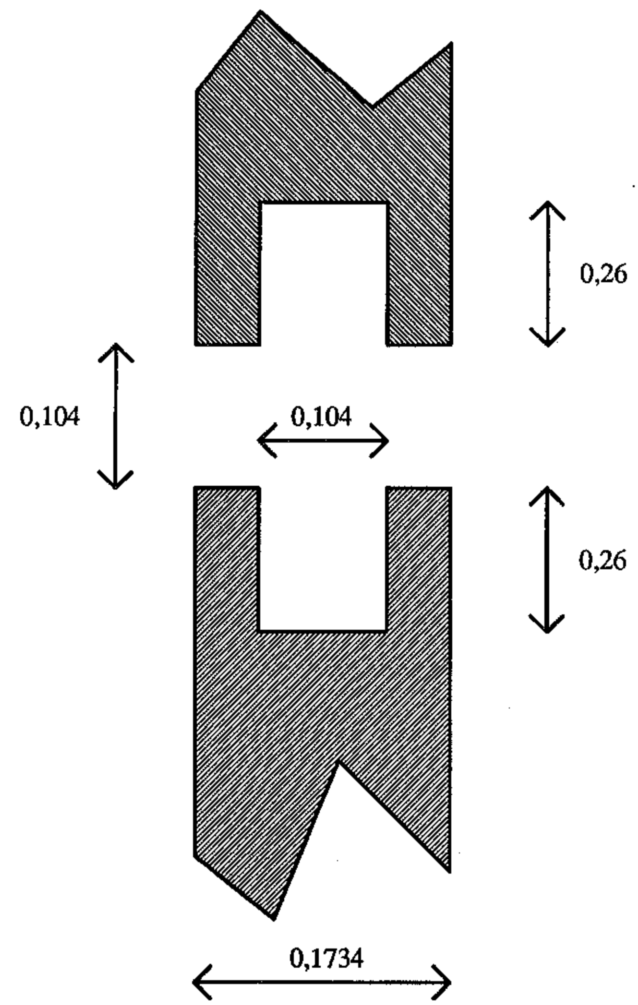

Figure 16. Corrugated slot. All dimensions in free space wavelength.

The geometry for the slot shown in figure 16 can be analysed as follows :

A. Define the geometry for the slot

- Choose Geometry - Define corrugations to bring forward the corrugations parameters dialog box.
- Choose Use corrugation by clicking the mouse in the brackets next to Yes.
- Input the parameters for defining the three rectangular sections of the cross section. The parameters should be :

$$N0 = N1 = N2 = N3 = 10$$
$$W1 = W3 = 0,104 \ ; \ T1 = T3 = 0,0347$$
$$W2 = 0,624 \ ; \ T2 = 0,104$$
$$Y2 = -0,26$$

- When all parameters are correct, choose OK or press Enter.

  Hint : you can control the parameters by selecting Geometry - Visualize corrugations by which a figure of the cross section will appear on the screen.

B. Define the excitation type

- Choose Excitation - Define type to bring forward the excitation dialog box.
- The number of basis functions is not applicable for the case of corrugations (defined in the corrugation parameters dialog box).
- Leave the incidence angle at zero degrees.
- Choose TE-polarisation.
- When all parameters are correct, choose OK or press Enter.

C. Perform calculation

- Choose Run - Run to bring forward the run confirmation dialog box.
- Be sure that the simulation type is "Corrugated slot". (If it is not see chapter 5.1).
- Press Yes for starting the computation.

When the calculation is ready the attenuation can be seen in the result window, it should be 39,75 dB. A significant increase, compared with the case without a corrugation (≈ 0 dB) ! However, it should be noted that the increase of attenuation is quite narrow banded.