Special Note for CONVEX and KSR users

1 CONVEX Users

To properly compile FEMA_CYL on a CONVEX machine, in addition to selecting the proper commands in the *Makefile* as described in the manual, the user must replace certain machine constants within the files: *rcs.f* and *dyadic.f*. To find the constants, use your editor to search for all occurrences of the name *CONVEX*. There is one occurrence in *dyadic.f* and two occurrences in *rcs.f*. Having found each instance, comment the preceeding two lines of code and uncomment the two lines which follow. These minor changes are required due to the reduced range of floating point number representation on the CONVEX architecture. The code should now compile without warnings or errors.

2 KSR Users

To properly compile FEMA_CYL on a KSR machine, in addition to selecting the proper commands in the *Makefile* as described in the manual, the user must uncomment certain lines in *fema_cyl.f* in order to exploit the parallel features of the program. The required lines lie within instances of *c#if* and *c#endif*. There are seven (7) occurrences. Do not uncomment the *c#if* or *c#endif* lines since the C preprocessor is not being used due to portability issues. The code should be ready to compile and run with a parallelized BiCG solver.

When running the code on a KSR, it is important to allocate the number of processors using the commands: *allocate_cells N* and
setenv PL_NUM_THREADS N where *N* is the number of processors.

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1 Introduction

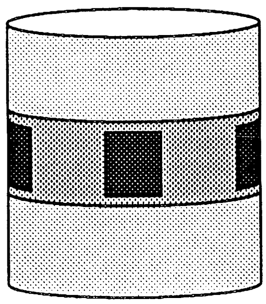
The Finite Element-Boundary Integral (FE-BI) technique has been used to analyze the scattering and radiation properties of cavity-backed patch antennas recessed in a metallic groundplane. A program, FEMA_RECT, was written and found to yield accurate results for large arrays without the usual high memory and computational demand associated with competing formulations. Recently, the FE-BI approach was extended to cavity-backed antennas recessed in an infinite, metallic circular cylinder. FEMA_CYL is a computer program written in the Radiation Laboratory of the University of Michigan which implements this formulation.

This user manual will give a brief introduction to FEMA_CYL and some hints as to its proper use. As with all computational electromagnetics programs (especially finite element programs), skilled use and best performance is only obtained through experience. However, we will comment on several important aspects of the program such as portability, geometry generation, interpretation of results and custom modification.

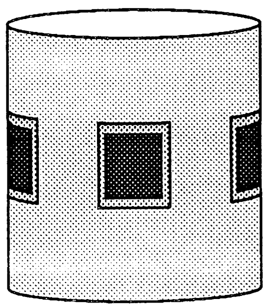
2 Formulation

FEMA_CYL implements the FE-BI formulation for cavity-backed antennas recessed in metallic circular cylinders. The formulation imposes some restrictions on the geometries which will be discussed. Principally, use of the BiConjugate Gradient-Fast Fourier Transform (BiCG-FFT) iterative solver requires uniform zoning on the aperture of the cavity. Thus, each surface patch has cylindrical-rectangular shape. The basis functions, dyadic Green's function and associated field formulas are given in a paper concerning scattering by these structures [1]. Modifications of this formulation for antenna analysis was given in another paper [2].

The uniform zoning requirement causes some difficulty in modeling; however, with some practice, these difficulties may be overcome. For example, the specification of the patch and cavity size must both be expressed by an integer number of edges (hence nodes). Thus, if the cavity is twice the size of the patch, one has no problem specifying the patch and the cavity with the same uniform grid. However, if the ratio of the patch and cavity sizes are not integers, discretization may not be possible. This is often the case with a continuous wraparound cavity. Such a cavity is shown in figure 1 along with an example of a discrete wraparound array. If the cavity size and patch size are not convenient, you must either change the cavity size as possible or change the radius of the cylinder. If the radius is changed slightly, it will not effect the electromagnetic properties of the structure, but it may allow uniform discretization. Although the restrictions imposed by the uniform zoning requirement seems rather stringent, with practice, an antenna designer will find that FEMA_CYL is quite flexible.



(a)



(b)

Figure 1: Illustration of two types of arrays: (a) continuous wraparound array; (b) discrete wraparound cavity array

3 Installation and Compilation

The first task in utilizing FEMA_CYL is to install the code on your computing platform. Two installation procedures are described, depending on the availability of a distribution tape or INTERNET access.

3.1 Installation Instructions

1. Place the distribution tape in the tape drive. If the drive is not the default archive device (`/dev/rmt/0h`), you need to find out the device unit number.

2. Retrieve the files from the tape to the appropriate directory. To install FEMA_CYL in the directory `fema_cyl.dir`, you need to say :

   ```
   mkdir fema_cyl.dir
   cd fema_cyl.dir
   tar xv *
   ```

   Note: If the drive is not the default archive device you would need to include the unit number; if you were using the device `/dev/rmt/4h` you will need to say :

   ```
   mkdir fema_cyl.dir
   cd fema_cyl.dir
   tar xv4 *
   ```

   This will place the following tar file in the `fema_cyl.dir` directory :

   ```
   fema_cyl.tar.Z
   ```

3. Uncompress `fema_cyl.tar.Z` by typing :

   ```
   uncompress fema_cyl.tar.Z
   ```

4. Untar `fema_cyl.tar` by typing :

   ```
   tar xvf fema_cyl.tar
   ```

5. You will now find the following files in fema_cyl.dir:

```
fema_cyl.f
dyadic.f
matrixGenerate.f
preProcessor.f
rcs.f
fft.f
fftCooley.f
fftSplitRadix.f
fftCRAY.f
fftCONVEX.f
gauss.inc
fft.inc
fftCRAY.inc
fema_cyl.inc
convertToASCII.f
Makefile
planarBuild
planarRun
```

   The functions of each of these files will be described in the subsection on compilation.

6. If you have INTERNET access, FEMA_CYL can be accessed by anonymous ftp. Type :

```
ftp gip.eecs.umich.edu
login: anonymous
password: <internet e-mail address>
cd people/bssunil
prompt off
mget *
quit
```

   Note: As access by anonymous ftp cannot be controlled, the authors of the code may need to be consulted before the code can be accessed.

3.2 Compilation

The next task in utilizing FEMA_CYL is to compile and link the various files of the program. The files generated as a result of the installation process perform the following functions:

- *fema_cyl.f*: Main program, BiCG solver, matrix building subroutines, FE-BI subroutine, impedance insert and various auxiliary subroutines.
- *dyadic.f*: Compute dyadic Green's function terms for admittance matrix, on-surface and far-field Fock functions and gamma function.
- *matrixGenerate.f*: Boundary integral and FE matrix terms.
- *preProcessor.f*: Geometry/mesh generator.
- *rcs.f*: Radar Cross Section, far-zone dyadic Green's function and plane wave excitation functions.
- *fft.f*: Forward and inverse Fast Fourier Transform subroutines.
- *gauss.inc*: Numerical integration parameters for gaussian quadrature.
- *fft.inc*: Include file for 2-D FFT subroutines.
- *fema_cyl.inc*: Main memory allocation file also contains variable dictionary.
- *fftCRAY.inc*: Include file for the Cray FFT library vectorized, multitasked 2-D FFTsubroutines.
- *planarBuild and planarRun*: Input data files for quasi-planar example geometry build and run.
- *Makefile*: Make file for the UNIX *make* utility.

In addition the following Fast Fourier Transform options are available :

- *fftCooley.f*: Classic Cooley-Tukey Radix-2 algorithm.
- *fftSplitRadix.f*: Split-Radix algorithm by Sorenson [3].
- *fftCRAY.f*: Calls the CRAY library vectorized, multitasked 2-D FFT routine.
- *fftCONVEX.f*: Calls the *veclib* vectorized 2-D FFT routine.

Prior to compilation, the user should copy one of these files into *fft.f*. The optimized routines for the CRAY and CONVEX architectures should be used when possible while in general the Split-Radix algorithm should give better performance than the Cooley-Tukey version. To enhance their efficiency, the Split-Radix and Cooley-Tukey files utilize a decimation-in-frequency forward transform and a decimation-in-time inverse transform in order to avoid the need for bit reversal.

Another file which is generated after installation is *convertToASCII.f*. To save disk space, the geometry information is stored in a binary format by *preprocessor*. The program *convertToASCII* is included to produce a human-readable file (ASCII). The nodes, elements, edges, unknowns and other useful information is provided in a easy to read (although disk space consuming) format. All the programs are compiled and linked by invoking the UNIX *make* utility. A *Makefile* has been generated during the installation process. To date, FEMA_CYL has been successfully compiled, linked and run on the following architectures/operating systems: SUN, DEC UNIX, HP 9000/7xx, IBM RS/6000, Silicon Graphics IRIS, CRAY, CONVEX and KSR. Three variable must be set within the *Makefile*:

- FF: The Fortran compiler name for the architecture.
- FOPT: The Fortran compiler options i.e. optimization, precision, etc.
- LOPT: The name of any libraries required for linking.

The user should uncomment these variables for the target architectures in *Makefile*. FEMA_CYL is constructed by simply typing *make* at the command line, while the binary-to-ASCII conversion program is constructed by entering *make convert*. FEMA_CYL is invoked by typing *fema_cyl* at the command line while the conversion program is run with the command *convertToASCII*. Finally, the directory may be cleaned up of all object and executable files by typing *make clean*.

3.3 Verification

Having compiled the code on your architecture, the distribution tape includes an example geometry build and run file which may be used to verify performance. These files are `planarBuild` and `planarRun` respectively. They contain the keyboard entries required to compute the bistatic radar cross-section of a 3.68 cm $\times$ 2.75 cm patch which is printed atop a 7.34 cm $\times$

5.33 cm $\times$ 0.01448 cm dielectric filled cavity with $\epsilon_r = 4.0$. To achieve a quasi-planar configuration, the cylinder radius is 65 cm. This geometry may be built by typing :

```
fema_cyl < planarBuild
```

at the UNIX prompt. The resulting geometry information is shown in figure 2.

```
Number of elements:  961
Total number of nodes:   2048
Total number of edges:   4992
Number of interior edges:   900
Number of metal edges:   2712
Number of aperture edges:   1380
     Resistive edges:   0
     Substrate edges:   1380
Number of unknowns:   2280
```

Figure 2: Geometry information for the quasi-planar configuration

Having built the test geometry, typing :

```
fema_cyl < planarRun
```

will compute the bistatic ($\theta_i = 90^0$, $\phi_i = 0^0$) scattering by this structure at 9.2 GHz for an E-polarized plane wave. The observation plane is $\phi = 0^0$. Figure 3 illustrates the pattern using the far-zone evaluation of either the cylindrical or planar Green's functions.

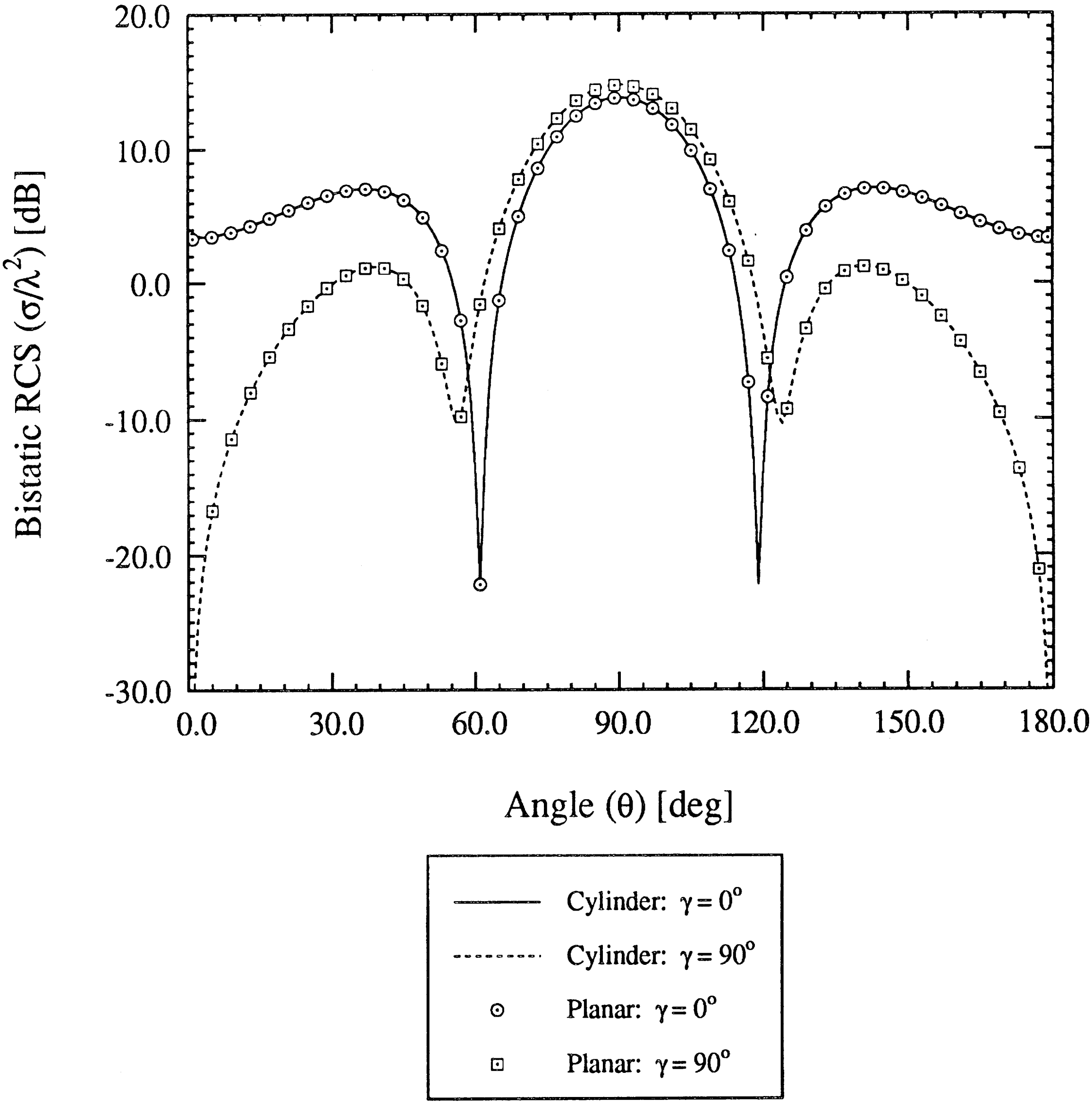


Figure 3: Bistatic RCS of a 3.68 cm × 2.75 cm patch on a 7.34 cm × 5.33 cm × 0.01448 cm cavity

4 Geometry Information

The binary geometry file created by *preprocessor* contains all the information concerning the physical structure under study except for the placement of any probe-feeds or lumped impedance posts. Therefore, it is important that the user be aware of the geometry entered into the FE-BI portion of the code. As previously mentions, the *convertToASCII* program creates a human-readable file from the machine-readable geometry file.

The first information provided in the resulting ASCII file is the header. which contains the number of nodes, number of edges, number of unknowns, etc. and an example of the header is shown in figure 4. The next field contains the node information. The information given is as follows (see figure 5):

- Column 1: Node number
- Column 2: Radial (ρ) coordinate in centimeters.
- Column 3: Angular (ϕ) coordinate in degrees.
- Column 3: Axial (z) coordinate in centimeters.
- Column 4: Layer number from top of the cylinder (aperture).
- Column 5: Row number from lowest axial coordinate.
- Column 6: Column number from smallest azimuthal coordinate.

Each node is associated with a physical location (ρ,ϕ,z) and a grid location (layer,row,column).

Grid points must be used in the discretization of a geometry since the BiCG-FFT solver requires that each node pair lie an integer number of units apart. Thus, the distance between two nodes (primed and unprimed) on the surface of the cylinder is given by

$$R(n,m;n',m') = \sqrt{(n-n')a\Delta\phi + (m-m')\Delta z} \qquad (1)$$

FEMA_CYL distinguishes between grid points and nodes. A grid point can be thought of as the intersection of two lines of a piece of graph paper which is placed on the surface of the cylinder. A node is a grid point which lies within a cavity. The row and column number associated with a node actually is the row and column number of the grid point which formed the node. The first grid point which corresponds to the lower-left corner of the grid has row

```
Binary filename:test.cyl


ASCII filename:test.ascii


NODE statistics:

Total number of nodes:  50
Number of nodes on the surface:  25
Number of nodes along the metallic walls:  41
Number of nodes on surface metallic patches:  0
Number of nodes which are resistive:  0


EDGE statistics:

Total number of edges:  105
Interior edges:  9
Aperture edges:  24
         a) substrate edges:  24
         b) resistive edges:  0
Metal edges (NOT unknowns):  72

||||||||| UNKNOWNS |||||||||-->   33


ELEMENT statistics:

Total number of elements:  16
Surface Elements:  16
```

Figure 4: Geometry header.

Node	rho(cm)	phi(deg)	z(cm)	layer	row	column
1	1.00000	-5.00000	-0.50000	0	0	0
2	1.00000	-2.50000	-0.50000	0	0	1
3	1.00000	0.00000	-0.50000	0	0	2
4	1.00000	2.50000	-0.50000	0	0	3
5	1.00000	5.00000	-0.50000	0	0	4
6	1.00000	-5.00000	-0.25000	0	1	0
7	1.00000	-2.50000	-0.25000	0	1	1
8	1.00000	0.00000	-0.25000	0	1	2
9	1.00000	2.50000	-0.25000	0	1	3
10	1.00000	5.00000	-0.25000	0	1	4
11	1.00000	-5.00000	0.00000	0	2	0
12	1.00000	-2.50000	0.00000	0	2	1
13	1.00000	0.00000	0.00000	0	2	2
14	1.00000	2.50000	0.00000	0	2	3
15	1.00000	5.00000	0.00000	0	2	4
16	1.00000	-5.00000	0.25000	0	3	0
17	1.00000	-2.50000	0.25000	0	3	1
18	1.00000	0.00000	0.25000	0	3	2
19	1.00000	2.50000	0.25000	0	3	3
20	1.00000	5.00000	0.25000	0	3	4
21	1.00000	-5.00000	0.50000	0	4	0
22	1.00000	-2.50000	0.50000	0	4	1
23	1.00000	0.00000	0.50000	0	4	2
24	1.00000	2.50000	0.50000	0	4	3
25	1.00000	5.00000	0.50000	0	4	4
26	0.90000	-5.00000	-0.50000	1	0	0
27	0.90000	-2.50000	-0.50000	1	0	1
28	0.90000	0.00000	-0.50000	1	0	2
29	0.90000	2.50000	-0.50000	1	0	3
30	0.90000	5.00000	-0.50000	1	0	4

<< Remainder of nodes truncated >>

Figure 5: Node information.

= 0 and column = 0. For a wraparound grid, the first grid point is physically located at $\varphi = -180^{\circ}$ and once again has row = 0 and column = 0.

The next set of information provided is the edges which form the cavities. The information given is as follows (see figure 6)

- Column 1: Edge number.
- Column 2: Left (lower) node forming the edge.
- Column 3: Right (upper) node forming edge.
- Column 3: Unknown number (zero indicates a fixed edge (e.g. metal)).
- Column 4: Orientation (ρ-, ϕ- or z-directed).
- Column 5: Type of edge (metal,substrate,resistive or interior).

Each edge is associated with two nodes and hence has an orientation in the cylindrical coordinate system. If an edge is metal, since FEMA_CYL uses a total field formulation, that edge's weight is fixed at zero. All other edges are unknowns which must be solved using the BiCG-FFT solver. A substrate or resistive edge is associated with the boundary integral while interior edges contribute only to the FE portion of the system. Currently, resistive cards are not implemented in FEMA_CYL.

The next set of information related the unknowns on the aperture of the cavities to their edge number. It also includes the row and column number of that edge in the discretization grid. Although this information is useful for understanding the mechanics of the BiCG-FFT solver, it is of little interest to the general user. The given information is (see figure 7)

- Column 1: Unknown number.
- Column 2: Associated edge number.
- Column 3: Row of this edge in the discretization.
- Column 3: Column of this edge in the discretization.

The edges which form each element of the mesh are given next. Each cylindrical shell element consists of eight nodes which form twelve edges. This information is useful in visualizing the mesh and could be hooked into a graphics package to generate a 3-D picture of the mesh. The prototype element is shown in figure 8 which displays the node numbering scheme. The information given by *convertToASCII* is (see figure 9)

- Row 1, Column 1: Element number.

Edge	Node 1	Node 2	Unknown	Orientation	Type
1	26	1	0	rho-directed	metal
2	27	2	0	rho-directed	metal
3	31	6	0	rho-directed	metal
4	32	7	25	rho-directed	interio
5	26	27	0	phi-directed	metal
6	1	2	0	phi-directed	metal
7	31	32	0	phi-directed	metal
8	6	7	1	phi-directed	substra
9	26	31	0	z-directed	metal
10	1	6	0	z-directed	metal
11	27	32	0	z-directed	metal
12	2	7	13	z-directed	substra
13	28	3	0	rho-directed	metal
14	33	8	26	rho-directed	interio
15	27	28	0	phi-directed	metal
16	2	3	0	phi-directed	metal
17	32	33	0	phi-directed	metal
18	7	8	2	phi-directed	substra
19	28	33	0	z-directed	metal
20	3	8	14	z-directed	substra
21	29	4	0	rho-directed	metal
22	34	9	27	rho-directed	interio
23	28	29	0	phi-directed	metal
24	3	4	0	phi-directed	metal
25	33	34	0	phi-directed	metal
26	8	9	3	phi-directed	substra
27	29	34	0	z-directed	metal
28	4	9	15	z-directed	substra
29	30	5	0	rho-directed	metal
30	35	10	0	rho-directed	metal

<< Remaining edges truncated >>

Figure 6: Edge information.

Unknown	Edge	Row	Column
1	8	2	1
2	18	2	3
3	26	2	5
4	34	2	7
5	40	4	1
6	47	4	3
7	52	4	5
8	57	4	7
9	63	6	1
10	70	6	3
11	75	6	5
12	80	6	7
13	12	1	2
14	20	1	4
15	28	1	6
16	44	3	2
17	49	3	4
18	54	3	6
19	67	5	2
20	72	5	4
21	77	5	6
22	90	7	2
23	95	7	4
24	100	7	6

Figure 7: Relationship between unknown number and edge number on aperture.

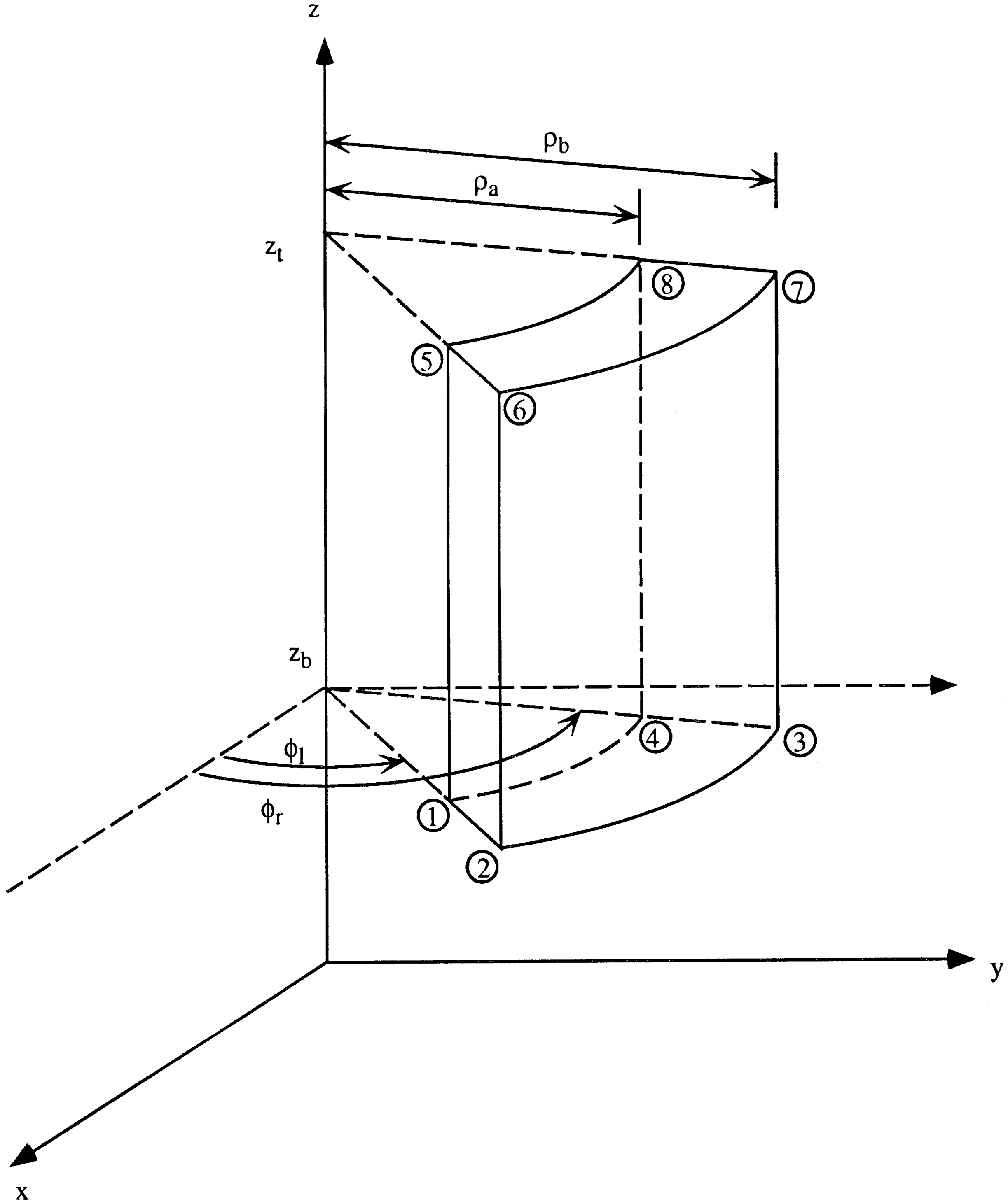


Figure 8: Cylindrical shell element.

- Row 1, Column 2-5: ρ-directed edges.
- Row 2, Column 2-5: ϕ-directed edges.
- Row 3, Column 2-5: z-directed edges.

The final set of information provided is the element parameters as shown in figure 8 which includes (see figure 10)

- Row 1: Element number.
- Row 2: ρ_a, ρ_b and t = $\rho_b - \rho_a$.
- Row 3: ϕ_l, ϕ_r and $\alpha = \phi_r - \phi_l$.
- Row 3: z_b, z_t and h = $z_t - z_b$.

5 Geometry Generation

Having reviewed the geometry information provided by *preprocessor* through *convertToASCII*, we are prepared to generate some example geometries. Specifically, we shall look at radiation and scattering by a 2 cm $\times$ 3 cm patch antenna which is placed in a 5 cm $\times$ 6 cm cavity, a four element discrete array of such cavities and the same radiating array placed in a continuous wraparound cavity. These three variations of the same geometry exhibit the main classes of structures encountered in practice. Users will find it very helpful to check the entered geometry via *convertToASCII* prior to running the solver part of FEMA_CYL. In particular, it is useful to discretize the cavity without patches present and retain the node information since it will be necessary to specify the row and column of the lower-left corner of each patch as well as the number of edges along each side.

FEMA_CYL has a *preprocessor* module which generates the required mesh. It first generates the surface nodes which are then used to create the 3-D mesh. A commercial modeling package, such as SDRC IDEAS, may be used to create such a surface grid so long as the nodes are an integer number of units apart. It would be quite easy to interface such a package with FEMA_CYL by replacing the subroutine *simpleMesh* with a universal file reader. However, we have found that the custom mesh routine provided with FEMA_CYL (*simpleMesh*) is sufficient for most modeling tasks while

Element	Edges			
1	1	2	3	4
	5	6	7	8
	9	10	11	12
2	2	13	4	14
	15	16	17	18
	11	12	19	20
3	13	21	14	22
	23	24	25	26
	19	20	27	28
4	21	29	22	30
	31	32	33	34
	27	28	35	36
5	3	4	37	38
	7	8	39	40
	41	42	43	44

<< Remaining elements truncated >>

Figure 9: Edges associated with each element.

```
Element size parameters:

  Element number:              1
     rhoA =     0.90000  rhoB =     1.00000     t =     0.10000
     phiL =    -5.00000  phiR =    -2.50000  alpha =     2.50000
      zB  =    -0.50000   zT  =    -0.25000     h   =     0.25000

  Element number:              2
     rhoA =     0.90000  rhoB =     1.00000     t =     0.10000
     phiL =    -2.50000  phiR =     0.00000  alpha =     2.50000
      zB  =    -0.50000   zT  =    -0.25000     h   =     0.25000

  Element number:              3
     rhoA =     0.90000  rhoB =     1.00000     t =     0.10000
     phiL =     0.00000  phiR =     2.50000  alpha =     2.50000
      zB  =    -0.50000   zT  =    -0.25000     h   =     0.25000

  Element number:              4
     rhoA =     0.90000  rhoB =     1.00000     t =     0.10000
     phiL =     2.50000  phiR =     5.00000  alpha =     2.50000
      zB  =    -0.50000   zT  =    -0.25000     h   =     0.25000

  Element number:              5
     rhoA =     0.90000  rhoB =     1.00000     t =     0.10000
     phiL =    -5.00000  phiR =    -2.50000  alpha =     2.50000
      zB  =    -0.25000   zT  =     0.00000     h   =     0.25000

                 << Remaining elements truncated >>
```

Figure 10: Element parameters.

being quite efficient. For this manual, we will use this package for all meshing requirements.

The first example is a 2 cm $\times$ 3 cm patch antenna recessed in a 5 cm $\times$ 6 cm cavity which is centered at ($\phi = 0^o$, z = 0 cm). The required information is as follows

- Choose item 1 (Preprocessor) from main menu.
- Enter radius of the cylinder in centimeters.
- Enter angular and axial size of grid in degrees and centimeters.
- Enter center of grid in degrees and centimeters.
- Enter number of grid points in azimuthal and axial directions.
- Enter number of identical cavities in the azimuthal and axial directions.
- Enter number of nodes per cavity.
- Indicate whether all surface nodes are metallic or resistive.
- Indicate whether all surface nodes are on the substrate (0 means a patch is present).
- Enter number of patches.
- Enter row and column of lower-left hand node of the patch (see node section of the geometry file for this information).
- Enter number of edges in (ϕ,z) directions for this patch.
- Indicate any additional metallic nodes (-999 2 denotes no remaining nodes).
- Enter number of substrate layers.
- For each layer, enter its thickness in centimeters.
- Enter 1 to save this geometry.
- Enter filename for this geometry.

The transcript for this geometry is shown on the following pages. The next two examples are a discrete array of these elements and a continuous wraparound array. The main difference is that the number of grid points is not the same as the number of nodes on the cavity surface. Essentially, the same information is entered as above with the exception that these two arrays have a wraparound (360^o) grid. See the attached transcripts for more details. Note for continuous wraparound cavities, if a patch crosses the branch cut ($\phi = \pm 180^o$), the nodes along the lower edge of the patch must be hand entered as shown in example 3. These nodes are obtained by running the *preprocessor* without specifying any patches and inspecting the human-readable geometry file. Note that for these three examples, the number of unknowns is dramatically different. For the single cavity of example 1, only 541 unknowns are required. The four identical discrete cavities requires 2164 unknowns which is of course 4×541. Finally, the continuous wraparound cavity has 12992 unknowns!

```
||||||||||||||||||||||||||||||||||||||||||||
|                                          |
|               Example 1                  |
|     Single Discrete Cavity Example       |
|                                          |
||||||||||||||||||||||||||||||||||||||||||||

 Do you wish to run:
                       1) Preprocessor
                       2) FEM-BI
                       3) Impedance aperture
                       0) Exit
1

 Performing initialization, please wait....

 Enter radius of cylinder (cm):
15.27887
 Enter array size (phi,z) in (deg,cm):
18.75 6
 Enter center of array (phi,z) in (deg,cm):
0 0
 Enter number of grid points in (phi,z) direction:
11 25

 Discretization:
                    deltaPhi =  1.875 deg
                    deltaZ   =  .25 cm

 Enter number of cavities in phi,z directions
1 1

 Enter number of nodes per cavity (phi,z):
11 25


 275 surface nodes have been generated...
 The node numbering has the following pattern

 SINGLE CAVITY:

    ^
    |   21   22   23   24   25
    |   16   17   18   19   20
    z   11   12   13   14   15
    |    6    7    8    9   10
    |    1    2    3    4    5
    ---------- phi ---------->

 if for example 25 nodes were specified.
 where node 13 is the center point.


 Now specify which other nodes are either:
              metallic
                 or
              resistive

 All surface nodes metal or resistive (1=yes):
0
 Are the nodes substrate nodes (1=yes):
0
 Enter number of metallic patches:
1
 Enter row,column of lower left corner of
 the patch on uniform grid for patch: 1
6 3
```

```
 Enter number of unknowns(edges) for each
 dimension (phi,z):
4 12

  << List of nodes constituting the patch deleted >>
  << Each of these nodes is specified by (phi,z) coord >>

 Now enter any individual nodes...
 Specify the class (metal or resistive) of all
 surface nodes which are NOT substrate nodes:
 Also indicate if 2 = metal or 3 = resistive...

 Enter node number (-999 if done):
-999 2

 0 resitive nodes entered...
 66 metal nodes entered...

 Enter number of substrate layers(INTEGER):
1

 Generating sub-surface nodes....
 Enter layer  1 thickness (cm):
0.07874

 All  550 NODES have now been created
 which form 240 elements...

 Generating edges...

 1303 edges generated....


 All element edges have been identified...

 Classifying edges....

 Number of elements: 240
 Total number of nodes:  550
 Total number of edges:  1303
 Number of interior edges:  207
 Number of metal edges:  762
 Number of aperture edges:  334
      Resistive edges:  0
      Substrate edges:  334
 Number of unknowns:  541

 Determining unknown order...

 Do you want to save this geometry (1=yes):
1
 Enter FEMA_CYL filename:
example1.cyl

 Writing binary FEMA_CYL file:
 example1.cyl

 Do you wish to run:
                      1) Preprocessor
                      2) FEM-BI
                      3) Impedance aperture
                      0) Exit
 0
```

```
|||||||||||||||||||||||||||||||||||||||||||||
|                                           |
|                 Example 2                 |
|       Four Discrete Cavities Example      |
|                                           |
|||||||||||||||||||||||||||||||||||||||||||||

 Do you wish to run:
                       1) Preprocessor
                       2) FEM-BI
                       3) Impedance aperture
                       0) Exit
1

 Performing initialization, please wait....

 Enter radius of cylinder (cm):
15.27887
 Enter array size (phi,z) in (deg,cm):
360 6
 Wrap-around cavity entered...
 Enter center of array (z) in (cm):
0
 Enter number of grid points in (phi,z) direction:
192 25

 Discretization:
                    deltaPhi =  1.875 deg
                    deltaZ   =  .25 cm

 Enter 1 if ring element, 0 if rectangular array:
0
 Enter number of cavities in phi direction
4

 Enter number of nodes per cavity (phi,z):
11 25
 Enter lower left-hand (row,column): 1
0 43
 Enter lower left-hand (row,column): 2
0 91
 Enter lower left-hand (row,column): 3
0 139
 Enter lower left-hand (row,column): 4
0 187


 1100 surface nodes have been generated...
 The node numbering has the following pattern

 AZMUTHAL CAVITY ARRAY:

   ^
   |
   |  19  20  21     22  23  24
   z  13  14  15     16  17  18
   |   7   8   9     10  11  12
   |   1   2   3      4   5   6
   ---------- phi ------------->

 if for example two 3x4 cavities
 were specified


 Now specify which other nodes are either:
            metallic
               or
```

```
              resistive

 All surface nodes metal or resistive (1=yes):
0
 Are the nodes substrate nodes (1=yes):
0
 Enter number of metallic patches:
4
 Enter row,column of lower left corner of
 the patch on uniform grid for patch: 1
6 46
 Enter number of unknowns(edges) for each
 dimension (phi,z):
4 12
 << Node list deleted >>
 Enter row,column of lower left corner of
 the patch on uniform grid for patch: 2
6 94
 Enter number of unknowns(edges) for each
 dimension (phi,z):
4 12
 << Node list deleted >>
 Enter row,column of lower left corner of
 the patch on uniform grid for patch: 3
6 142
 Enter number of unknowns(edges) for each
 dimension (phi,z):
4 12
 << Node list deleted >>
 Enter row,column of lower left corner of
 the patch on uniform grid for patch: 4
6 190
 Enter number of unknowns(edges) for each
 dimension (phi,z):
4 12
 << Node list deleted >>
 Now enter any individual nodes...
 Specify the class (metal or resistive) of all
 surface nodes which are NOT substrate nodes:
 Also indicate if 2 = metal or 3 = resistive...

 Enter node number (-999 if done):
-999 2

 0 resitive nodes entered...
 261 metal nodes entered...

 Enter number of substrate layers(INTEGER):
1

 Generating sub-surface nodes....
 Enter layer  1 thickness (cm):
0.07874

 All  2200 NODES have now been created
 which form 960 elements...

 Generating edges...

 5212 edges generated....


 All element edges have been identified...



 Classifying edges....
```

```
 Number of elements: 960
 Total number of nodes:  2200
 Total number of edges:  5212
 Number of interior edges:  828
 Number of metal edges:  3048
 Number of aperture edges:  1336
      Resistive edges:  0
      Substrate edges:  1336
 Number of unknowns:  2164

 Determining unknown order...


 Do you want to save this geometry (1=yes):
1
 Enter FEMA_CYL filename:
example2.cyl

 Writing binary FEMA_CYL file:
 example2.cyl

 Do you wish to run:
                     1) Preprocessor
                     2) FEM-BI
                     3) Impedance aperture
                     0) Exit
0
```

```
        ||||||||||||||||||||||||||||||||||||||||||||
        |                                          |
        |                Example 3                 |
        |     Four Patches on Continuous           |
        |     Wraparound Cavity Example            |
        |                                          |
        ||||||||||||||||||||||||||||||||||||||||||||

 Do you wish to run:
                      1) Preprocessor
                      2) FEM-BI
                      3) Impedance aperture
                      0) Exit
1

 Performing initialization, please wait....

 Enter radius of cylinder (cm):
15.27887
 Enter array size (phi,z) in (deg,cm):
360 6
 Wrap-around cavity entered...
 Enter center of array (z) in (cm):
0
 Enter number of grid points in (phi,z) direction:
192 25

 Discretization:
                   deltaPhi =  1.875 deg
                   deltaZ   =  .25 cm

 Enter 1 if ring element, 0 if rectangular array:
1
 Enter number of identical rings (>=1):
1 Enter number of nodes per cavity (phi,z):
192 25
 Enter lower left-hand (row,column): 1
0 0


 4800 surface nodes have been generated...
 The node numbering has the following pattern

 SINGLE CAVITY:

   ^
   |   21   22   23   24   25
   |   16   17   18   19   20
   z   11   12   13   14   15
   |    6    7    8    9   10
   |    1    2    3    4    5
   ---------- phi ---------->

 if for example 25 nodes were specified.
 where node 13 is the center point.


 Now specify which other nodes are either:
             metallic
                or
             resistive

 All surface nodes metal or resistive (1=yes):
0
 Are the nodes substrate nodes (1=yes):
0
 Enter number of metallic patches:
```

```
4
 Enter row,column of lower left corner of
 the patch on uniform grid for patch: 1
6 46
 Enter number of unknowns(edges) for each
 dimension (phi,z):
4 12
   << Metallic node list deleted >>
 Enter row,column of lower left corner of
 the patch on uniform grid for patch: 2
6 94
 Enter number of unknowns(edges) for each
 dimension (phi,z):
4 12
   << Metallic node list deleted >>
 Enter row,column of lower left corner of
 the patch on uniform grid for patch: 3
6 142
 Enter number of unknowns(edges) for each
 dimension (phi,z):
4 12
   << Metallic node list deleted >>
 Enter row,column of lower left corner of
 the patch on uniform grid for patch: 4
6 190
 Enter number of unknowns(edges) for each
 dimension (phi,z):
4 12
 This patch includes branch...
 Enter first row nodes:
1343
 1343 176.25 -1.5
1344
 1344 178.1249 -1.5
1153
 1153 -180.0 -1.5
1154
 1154 -178.125 -1.5
1155
   << Metallic node list deleted >>
 Now enter any individual nodes...
 Specify the class (metal or resistive) of all
 surface nodes which are NOT substrate nodes:
 Also indicate if 2 = metal or 3 = resistive...

 Enter node number (-999 if done):
-999 2

 0 resitive nodes entered...
 261 metal nodes entered...

 Enter number of substrate layers(INTEGER):
1

 Generating sub-surface nodes....
 Enter layer  1 thickness (cm):
0.07874

 All  9600 NODES have now been created
 which form 4584 elements...

 Generating edges...

 23616 edges generated....

 All element edges have been identified...
```

```
 Classifying edges....

 Number of elements: 4608
 Total number of nodes:  9600
 Total number of edges:  23616
 Number of interior edges:  4416
 Number of metal edges:  10624
 Number of aperture edges:  8576
      Resistive edges:  0
      Substrate edges:  8576
 Number of unknowns:  12992

 Determining unknown order...


 Do you want to save this geometry (1=yes):
1
 Enter FEMA_CYL filename:
example3.cyl

 Writing binary FEMA_CYL file:
 example3.cyl

 Do you wish to run:
                      1) Preprocessor
                      2) FEM-BI
                      3) Impedance aperture
                      0) Exit
0
```

6 Operation Modes

FEMA_CYL has three main operation modes for FE-BI calculations (option 2 from the main menu). They are: input impedance vs. frequency, radiation pattern or RCS vs. frequency and single frequency radiation and RCS pattern calculations. This section will describe each mode using example 1 above.

6.1 Input Impedance – Multiple Frequencies

The first option presented is calculation of a patch antenna's input impedance at multiple frequencies. This is most useful in determining the resonant frequency of a patch antenna. The following information is required

- Choose item 2 (FE-BI) from main menu.
- Enter the stored binary geometry file.
- Enter 0 for cylindrical far-zone Green's function or 1 for planar far-zone Green's function
- Enter 1 if all elements have the same material parameters.
- Enter complex permittivity.
- Enter complex permeability.
- Enter BiCG convergence tolerance, minimum and maximum number of iterations.
- Enter 1 to monitor convergence.
- Enter 1 for diagonal preconditioning and 0 for no preconditioning.
- Enter 1 for frequency sweep of the input impedance.
- Enter name of file to store the input impedance.
- Enter number of probe feeds.
- Enter location of each feed in terms of (ϕ=degrees, z=cm).
- Enter which layer in which the feed is embedded.
- Enter complex current for this feed.
- Enter number of impedance post loads.
- Enter frequency range (in GHz) for this sweep.
- Return to main menu.

The input impedance for 3.1 GHz to 3.3 GHz computed every 10 MHz is shown in figure 11. The transcript for computing the input impedance of an axially polarized 2 cm $\times$ 3 cm patch in a 5 cm $\times$ 6 cm cavity is given on the following page.

```
 Do you wish to run:
                         1) Preprocessor
                         2) FEM-BI
                         3) Impedance aperture
                         0) Exit
2

 Performing initialization, please wait....

 Enter FEMA_CYL filename:
example1.cyl
 Reading excalibur file: example1.cyl

 Is this geometry quasi-planar (0=no,1=yes):
0
 Material Parameter Specification....
 Is the material filling constant (1=yes,0=no)?
1
 Enter relative permittivity [real,imaginary]:
2.17 0
 Enter relative permeability [real,imaginary]:
1 0

 Checking dimension allocations...

 Number of Boundary Integral Unknowns: 334
 Total number of UNKNOWNS: 541

Enter tolerance, minimum and maximum iterations:
0.01 2 500
 Do you wish to monitor convergence (0=no,1-yes)?
0
 Do you want:  0 = no preconditioning, 1 = diagonal?
1
 Do you want to compute:
      0 = RCS/Pattern, 1 = Zin, 2 = Freq. Sweep?
1
 Enter Zin filename:
example1.zin

 ||||||||||||||||||||||||||||||||||||||||
 |     PROBE FEED INFORMATION           |
 ||||||||||||||||||||||||||||||||||||||||

 Enter number of feeds:
1
 Enter feed location (phi,z) in (deg,cm):
0 -0.375
 Enter layer number of feed <=: 1
1
 Enter mag,phase of probe current (amp,deg):
1 0

 ||||||||||||||||||||||||||||||||||||||||
 |     IMPEDANCE LOAD INFORMATION       |
 ||||||||||||||||||||||||||||||||||||||||

 Enter number of loads:
0

 Enter start,stop and increment freq. (GHz):
3.1 3.3 0.01
 << Data shown in attached figure >>
```

6.2 Pattern – Multiple Frequencies

The next option presented is calculation of a radiation or RCS pattern at multiple frequencies. This is useful in computing the variation of gain or RCS with respect to frequency. Usually, a single observation angle is specified although multiple angles are allowed. This mode permits radiation, bistatic and backscatter computations. In addition, the input impedance as a function of frequency is stored if a probe feed is used for excitation. In this example, we compute the backscatter at normal incidence for an E_z-polarized plane wave as a function of frequency. The required information is

- Choose item 2 (FE-BI) from main menu.
- Enter the stored binary geometry file.
- Enter 0 for cylindrical far-zone Green's function or 1 for planar far-zone Green's function
- Enter 1 if all elements have the same material parameters.
- Enter complex permittivity.
- Enter complex permeability.
- Enter BiCG convergence tolerance, minimum and maximum number of iterations.
- Enter 1 to monitor convergence.
- Enter 1 for diagonal preconditioning and 0 for no preconditioning.
- Enter 2 for frequency sweep of the far-zone fields.
- Enter name of file to store the input impedance.
- Enter name of file to store the RCS or Gain.
- Enter observation type (0 = backscatter).
- Enter start, stop and increment azimuth (ϕ) angles (in degrees).
- Enter start, stop and increment elevation (θ) angles (in degrees).
- Enter polarization angle (0 = E-pol, 90 = H-pol).
- Enter RCS filename.
- Enter number of probe feeds.
- Enter number of impedance post loads.
- Enter frequency range (in GHz) for this sweep.
- Return to main menu.

The RCS for 3.1 GHz to 3.3 GHz computed every 10 MHz is shown in figure 12. The transcript for backscatter calculations for backscatter calculations is shown on the next page.

```
Do you wish to run:
                    1) Preprocessor
                    2) FEM-BI
                    3) Impedance aperture
                    0) Exit
:
Performing initialization, please wait....

Enter FEMA_CYL filename:
xample1.cyl
Reading fema_cyl file: example1.cyl
Is this geometry quasi-planar (0=no,1=yes):

Material Parameter Specification....
Is the material filling constant (1=yes,0=no)?

Enter relative permittivity [real,imaginary]:
:.17 0
Enter relative permeability [real,imaginary]:
 0
Checking dimension allocations...
Number of Boundary Integral Unknowns: 334
Total number of UNKNOWNS: 541
nter tolerance, minimum and maximum iterations:
.01 2 500
Do you wish to monitor convergence (0=no,1-yes)?

Do you want:  0 = no preconditioning, 1 = diagonal?

Do you want to compute:
     0 = RCS/Pattern, 1 = Zin, 2 = Freq. Sweep?

Enter Zin filename:
est.zin
Enter Frequency sweep data filename:
xample1.fsw
Enter observation type:
                         0) Backscatter
                         1) Bistatic
                         2) Radiation


Enter start,stop, and increment azmuth angles [deg]:
 0 1
Enter start,stop,and increment elevation angles [deg]:
0 90 1
Enter polarization angle [0 <= alpha <= 90 deg]:
           Ephi=0:  alpha = 0
           Etheta=0:  alpha = 90

Enter ouput RCS filename [<= 40 characters]:
unk

||||||||||||||||||||||||||||||||||||||||
|     PROBE FEED INFORMATION            |
||||||||||||||||||||||||||||||||||||||||

Enter number of feeds:

||||||||||||||||||||||||||||||||||||||||
|     IMPEDANCE LOAD INFORMATION        |
||||||||||||||||||||||||||||||||||||||||

Enter number of loads:

Enter start,stop and increment freq. (GHz):
.1 3.3 0.01
```

6.3 Pattern – Single Frequency

The final operation mode is radiation and RCS pattern calculations at a single frequency. Of course, for the case of an antenna, the input impedance is also computed. This mode is generally used for multiple incident and observation angle applications. The only difference between this mode and the previous two modes is the option to save the admittance matrix in binary format. Since this matrix is excitation independent (though still frequency dependent), it can save time for multiple runs of a large geometry if this matrix is stored and then read in for each run. The required inputs are

- Choose item 2 (FE-BI) from main menu.
- Enter the stored binary geometry file.
- Enter 0 for cylindrical far-zone Green's function or 1 for planar far-zone Green's function
- Enter 1 if all elements have the same material parameters.
- Enter complex permittivity.
- Enter complex permeability.
- Enter BiCG convergence tolerance, minimum and maximum number of iterations.
- Enter 1 to monitor convergence.
- Enter 1 for diagonal preconditioning and 0 for no preconditioning.
- Enter 0 for single frequency operation.
- Enter matrix storage/read option(1 to store, 2 to read, 0 to do nothing).
- Enter six (6) character filename for matrix storage/read.
- Enter observation type (1 = bistatic).
- Enter incidence angle (ϕ,θ).
- Enter start, stop and increment azimuth (ϕ) angles (in degrees).
- Enter start, stop and increment elevation (θ) angles (in degrees).
- Enter polarization angle (0 = E-pol, 90 = H-pol).
- Enter RCS filename.
- Enter number of probe feeds.
- Enter number of impedance post loads.

- Enter frequency (in GHz).
- Return to main menu.

This option is illustrated in the next session transcript for bistatic scattering and radiation pattern calculations.

```
 Do you wish to run:
                      1) Preprocessor
                      2) FEM-BI
                      3) Impedance aperture
                      0) Exit
2
 Performing initialization, please wait....
 Enter FEMA_CYL filename:
example1.cyl
 Reading fema_cyl file: example1.cyl
 Is this geometry quasi-planar (0=no, 1=yes):
0
 Material Parameter Specification....
 Is the material filling constant (1=yes,0=no)?
1
 Enter relative permittivity [real,imaginary]:
2.17 0
 Enter relative permeability [real,imaginary]:
1 0
 Checking dimension allocations...
 Number of Boundary Integral Unknowns: 334
 Total number of UNKNOWNS: 541
Enter tolerance, minimum and maximum iterations:
0.01 2 500
 Do you wish to monitor convergence (0=no,1-yes)?
0
 Do you want:  0 = no preconditioning, 1 = diagonal?
1
 Do you want to compute:
      0 = RCS/Pattern, 1 = Zin, 2 = Freq. Sweep?
0
 Save the BI arrays in a file (0=no,1=yes,2=read)?
1
 All BI files will have the following form:
 <filename>.guu,<filename>.guv, etc.
 Enter BI binary filename(must be six(6) char):
exampl
 Enter observation type:
                           0) Backscatter
                           1) Bistatic
                           2) Radiation
1
 Enter incident phi,theta [deg]:
0 90
 Enter start,stop, and increment azmuth angles [deg]:
-180 180 1
 Enter start,stop,and increment elevation angles [deg]:
90 90 1
 Enter polarization angle [0 <= alpha <= 90 deg]:
           Ephi=0:  alpha = 0
           Etheta=0:  alpha = 90
0
 Enter ouput RCS filename [<= 40 characters]:
exampl.bi
 Enter frequency (GHz):
3.3
 ||||||||||||||||||||||||||||||||||||||||
 |     PROBE FEED INFORMATION           |
 ||||||||||||||||||||||||||||||||||||||||

 Enter number of feeds:
1
 Enter feed location (phi,z) in (deg,cm):
0 -0.375
 Enter layer number of feed <=: 1
1
 Enter mag,phase of probe current (amp,deg):
```

```
1 0

 ||||||||||||||||||||||||||||||||||||||||||
 |     IMPEDANCE LOAD INFORMATION        |
 ||||||||||||||||||||||||||||||||||||||||||

 Enter number of loads:
0
 Writing BI binary files...
 Generate bistatic excitation vector...
 Solve it...

  << Pattern deleted. >>

 Run anouther excitation? (1=yes,0=no)
1

 Enter observation type:
                          0) Backscatter
                          1) Bistatic
                          2) Radiation
2
 Enter start,stop, and increment azmuth angles [deg]:
-180 180 1
 Enter start,stop,and increment elevation angles [deg]:
90 90 1
 Enter ouput RCS filename [<= 40 characters]:
exampl.pat
 Enter normalized pattern filename:
exampl.norm
 Solve it...
  << Pattern deleted. >>
 Run anouther excitation? (1=yes,0=no)
0

 Do you wish to run:
                     1) Preprocessor
                     2) FEM-BI
                     3) Impedance aperture
                     0) Exit
0
```

The bistatic patterns taken at 3.3 GHz for the three geometry configurations presented in this manual are shown in figure 13 The corresponding antenna pattern comparisonat 3.3 GHz is shown in figure 14

7 Slot Antenna Calculations

A problem which was analysed using FEMA_CYL was the radiation from a single folded slot on a cylindrical platform [4]. This example serves as a demonstration of the versatility of the code. By solving a problem involving more than 60K unknowns it demonstrated the scalability of the code. It also serves as an excellent tool to understand the use of the code.

The geometry of the problem is indicated in Figure 15. The side-walls and the base of the cavity were loaded with absorber to eliminate the effect of the cavity. The absorber-coating on the sidewalls was 0.2λ thick(@ 2GHz) with the coating being placed 0.2λ from the slot. Sampling and placement of absorber in the vertical direction in the cavity is shown in Figure 16. It was found that in this direction an absorber of thickness 0.15λ placed at a distance of 0.3λ guaranteed convergence. When mounted on a cylindrical platform, the geometry is as depicted in Figure 17. The modeling of the aperture as a collection of metallic patches is shown in Figure 18 and a table useful in feeding correct data to the code is shown in Table 1. A similar table for sampling and material properties along the depth of the cavity is shown in Table 2. The aperture after discretization and the resulting run statistics are shown in Figure 19. While finding the slot impedance as a function of frequency, the transcript of a typical session with FEMA_CYL is given in Appendix A. Some generated results are shown in Figures 20 and 21. The slot in Figure 20 has a slot separation of 0.77216 cm while that in Fig 21 has a separation of 0.38608 cm.

8 Concluding Remarks

This user manual presented some basic operation information for the FE-BI code, FEMA_CYL. This presentation was only meant to get an initial user started. As one becomes experienced with the code, additional features such as 2-D patch array modeling, multiple feed arrays and use of lumped impedance loads may prove useful. Indeed, an experienced user will find that custom features may readily be added to FEMA_CYL. For example, currently FEMA_CYL allows entry of material parameters either for the entire substrate, each layer of the substrate or on an element-by-element basis. This subroutine *material* in file *fema_cyl.f* may readily be modified by the user to input a custom inhomogeneous substrate.

The code is fairly "dummy proof". If the user enters data which is not expected by FEMA_CYL such as a character when an integer is expected or an angle greater than 360^o, the code will prompt the user to re-enter the requested data. Additionally, the storage allocation parameters in *fema_cyl.inc* must be set by the user prior to compilation. If a particular parameter is too small for a given run, the code will halt and suggest a new value for the offensive parameter. The user must reset that parameter, recompile and run the code again. The program also estimates the amount of RAM required at the start of a run. This estimate is based on the storage required by the arrays in *fema_cyl.inc* plus some scratch arrays. Each complex number is assumed to require eight bytes and each integer and real number require four bytes. The user should consider this estimate to be a slightly lower than the actual consumed memory.

References

[1] L.C. Kempel and J.L. Volakis, "Scattering by cavity-backed antennas on a circular cylinder," submitted to *IEEE Trans. Antennas and Propagat.*.

[2] L.C. Kempel, J.L. Volakis and R. Sliva, "Radiation by cavity-backed antennas on a circular cylinder," to be submitted.

[3] Sorenson *et al*, *IEEE Trans. Acoustics, Speech and Signal Processing*, pp. 152-156, Feb. 1986.

[4] M.W. Nurnberger, S. Bindiganavale, L.C. Kempel, J.L. Volakis and J. Mosko, *Analysis of a log-periodic folded slot antenna array on planar and cylindrical platforms*, Radiation Lab Rep. # 031169-1-T, Univ. Of Michigan, March 1994.

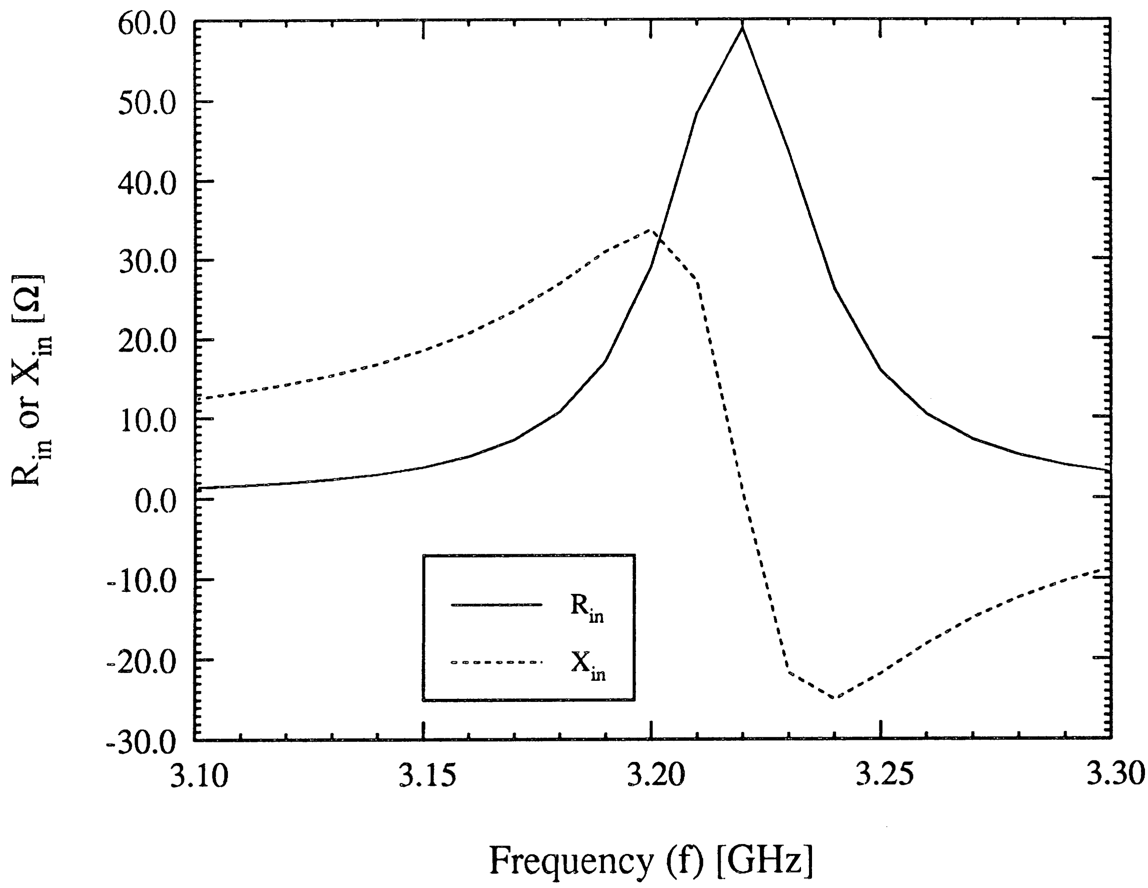


Figure 11: Input impedance vs. frequency for the axially polarized patch antenna which is 2 cm × 3 cm in a 5 cm × 6 cm cavity.

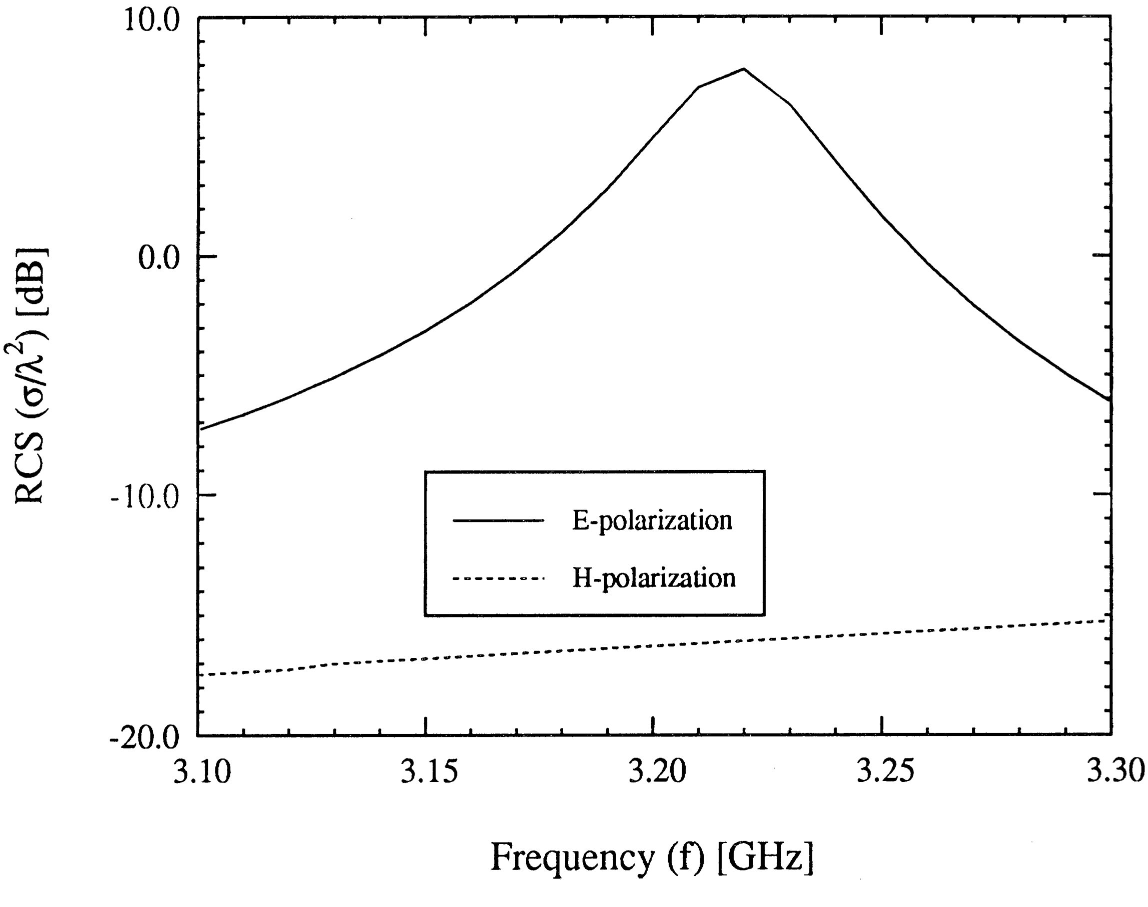


Figure 12: RCS vs. frequency for a patch antenna which is 2 cm $\times$ 3 cm in a 5 cm $\times$ 6 cm cavity.

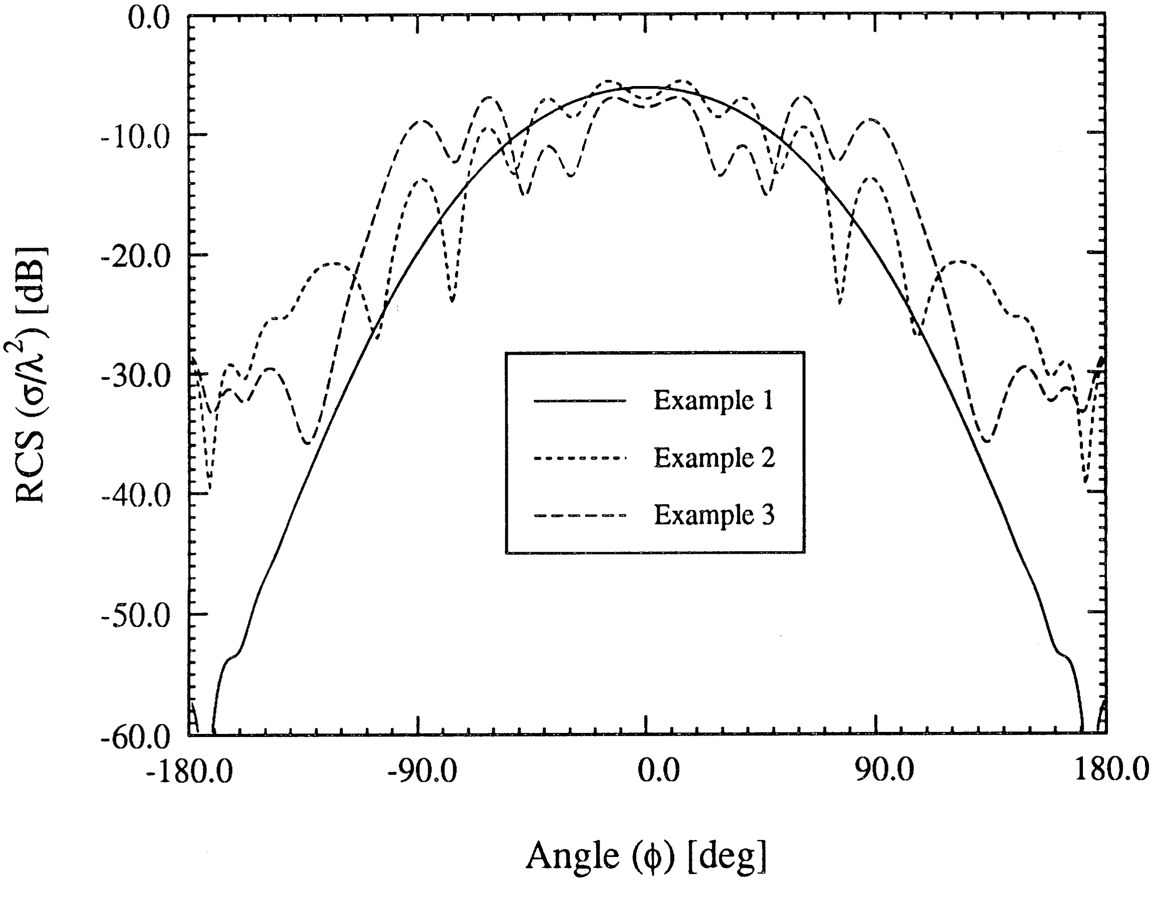


Figure 13: E-polarized bistatic patterns for a 2 cm $\times$ 3 cm embedded in the three different geometries presented in this manual. The incidence angle is $(0^o, 90^o)$ and observation is in the $\theta = 90^o$ plane.

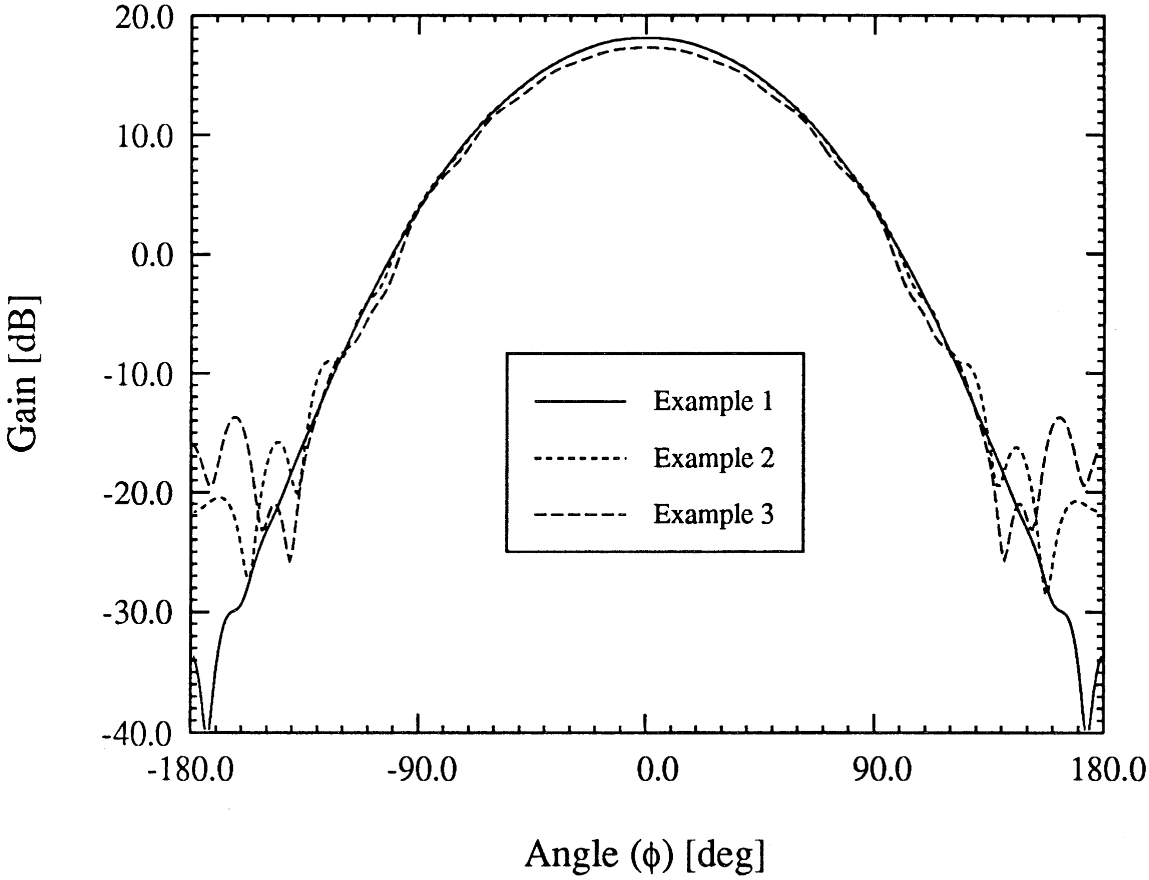


Figure 14: Axially polarized H-plane patterns for a 2 cm $\times$ 3 cm embedded in the three different geometries presented in this manual.

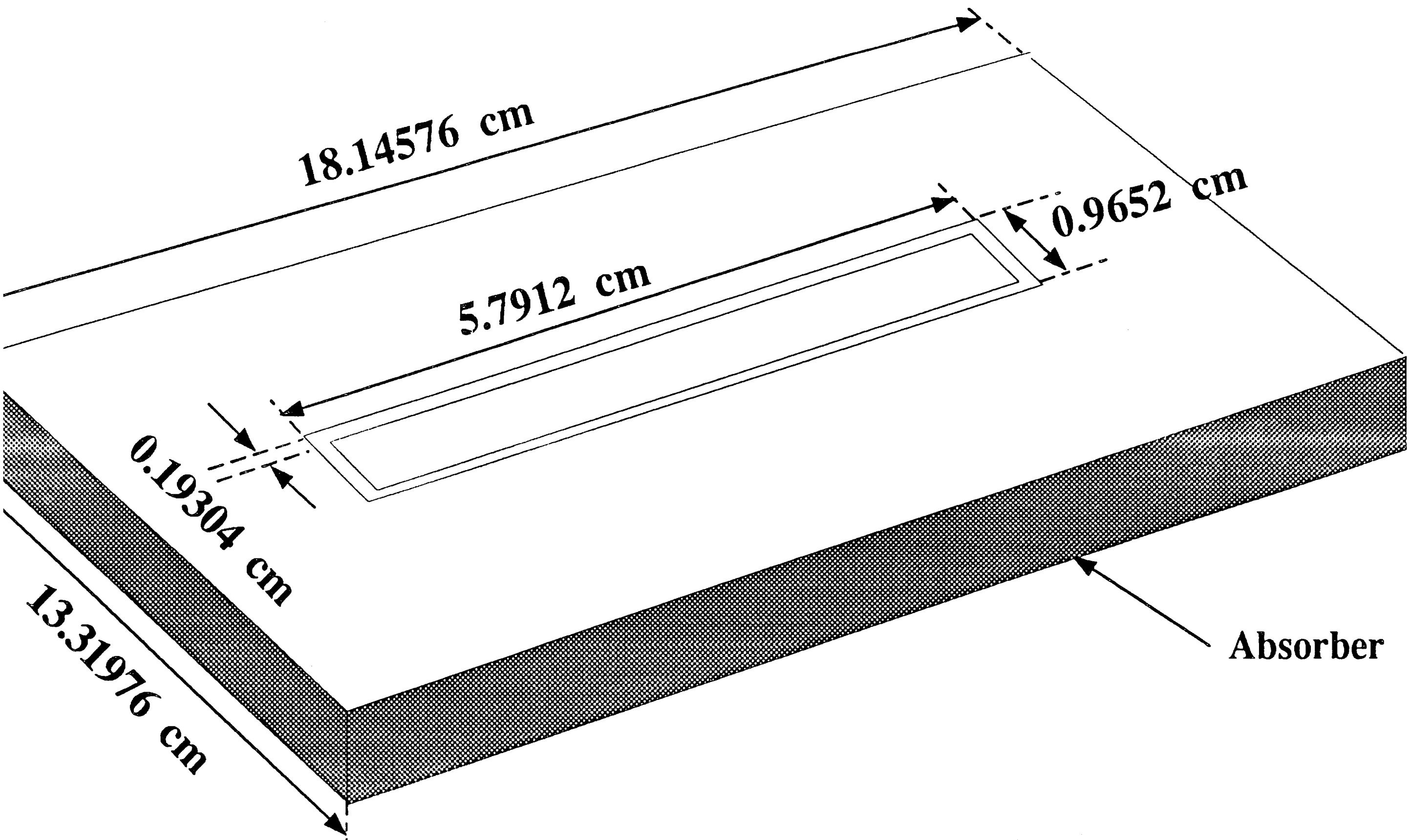


Figure 15: Geometry of the planar folded slot, showing the dielectric substrate

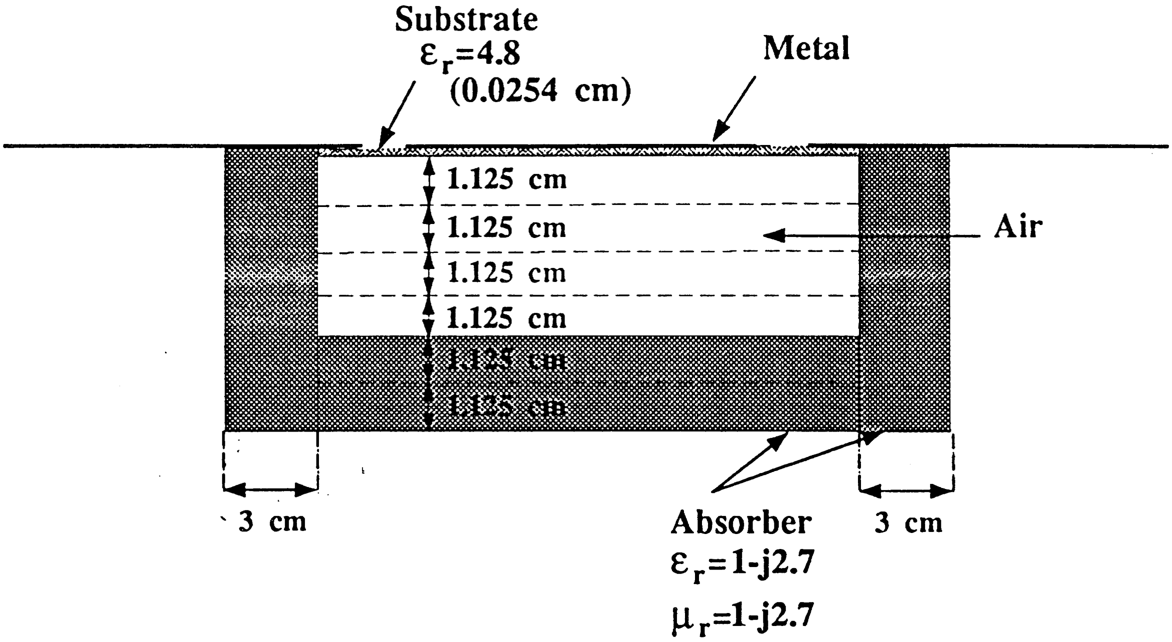


Figure 16: Geometry of the planar folded slot, showing the absorber-lined cavity

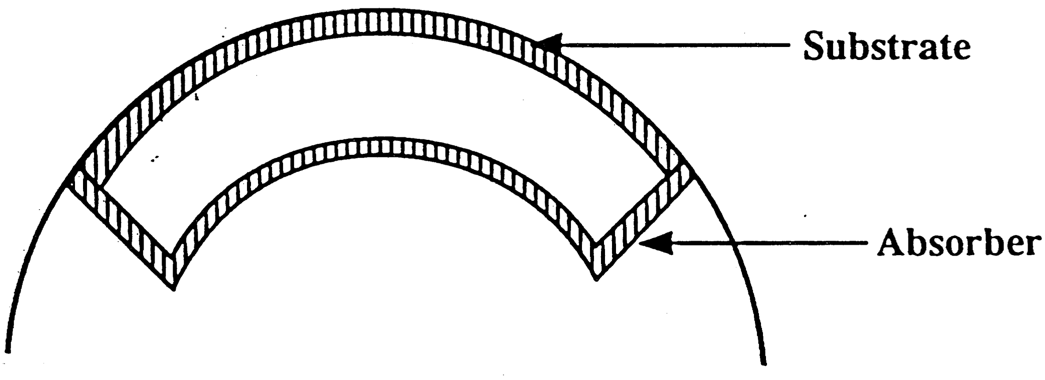


Figure 17: Geometry of the folded slot when mounted on a cylinder

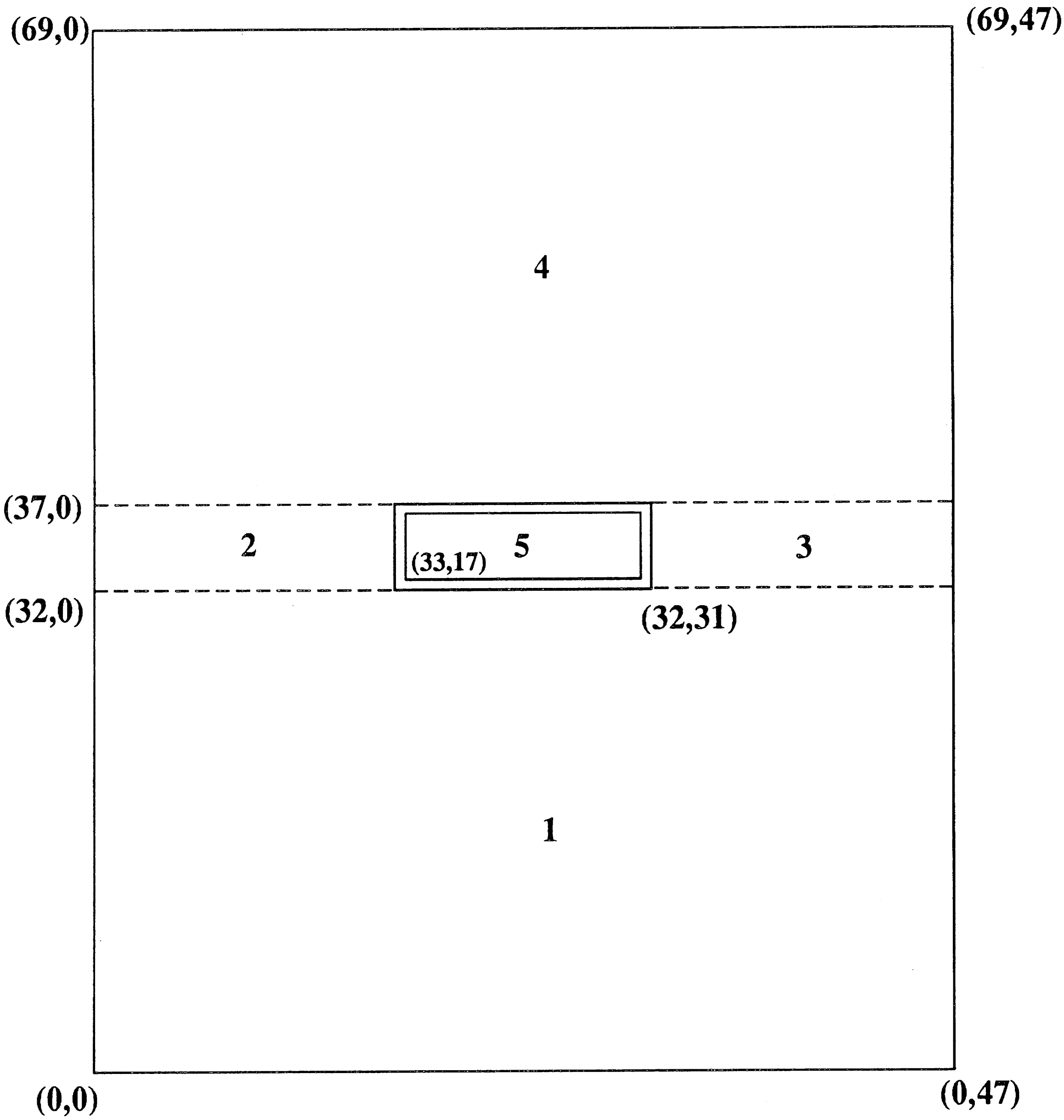


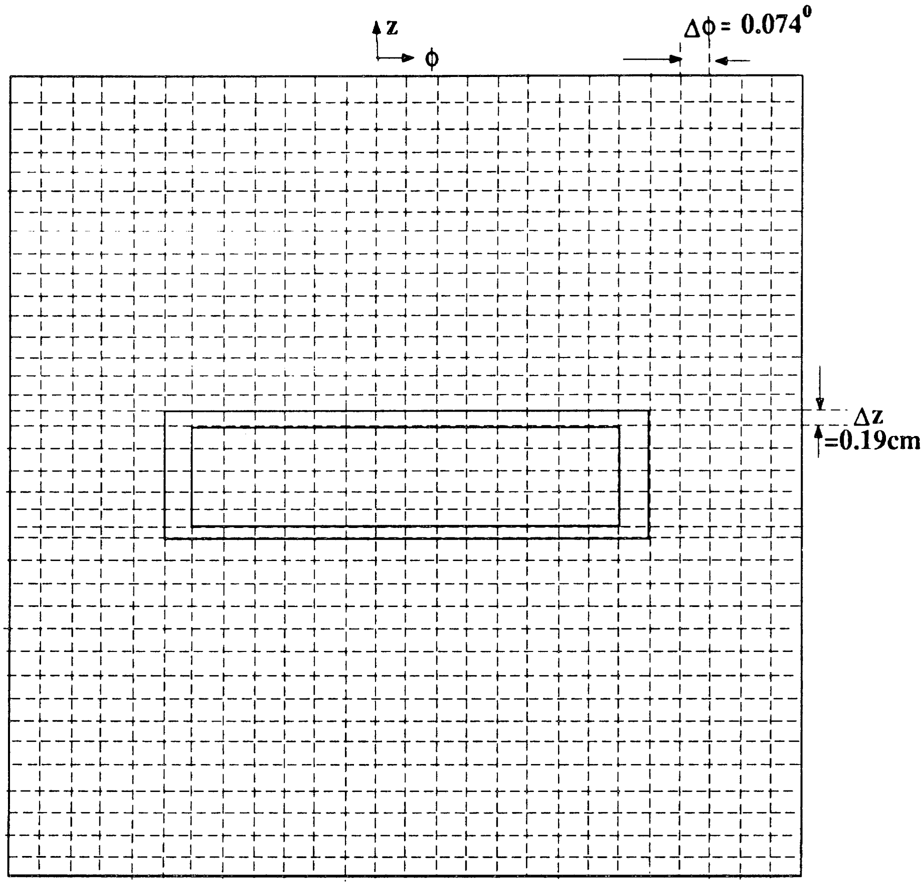
Figure 18: Modeling of the aperture as a collection of patches

Patch no.	*Lower left corner (node nos.)*	*Size(edges)*
1	(0,0)	47×32
2	(32,0)	16×5
3	(32,31)	16×5
4	(37,0)	47×32
5	(33,17)	13×3

Table 1: Table specifying patch sizes and locations for the folded slot problem

Layer no.	*Thickness (cm)*	ϵ_r, μ_r
1	0.0254	4.8,1
2	1.125	1,1
3	1.125	1,1
4	1.125	1,1
5	1.125	1,1
6	1.125	1-j2.7, 1-j2.7
7	1.125	1,-j2.7,1-j2.7

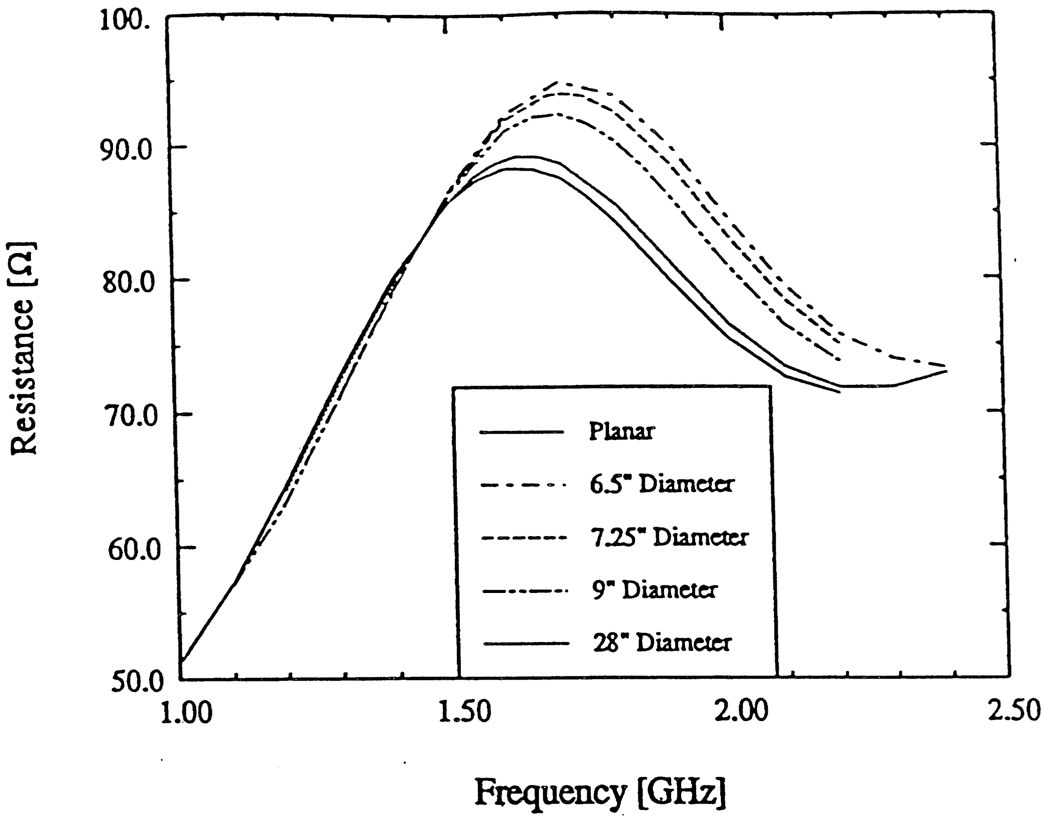
Table 2: Table specifying sampling and material properties in the cavity



RUN STATISTICS :

NODES ~ 26,880
ELEMENTS ~ 22,701
METAL NODES ~ 3,428
EDGES ~ 76,336
INTERIOR EDGES ~ 60,116
METAL EDGES ~ 16,184
APERTURE EDGES ~ 36
UNKNOWNS ~ 60,152

Figure 19: Final discretization of the antenna aperture



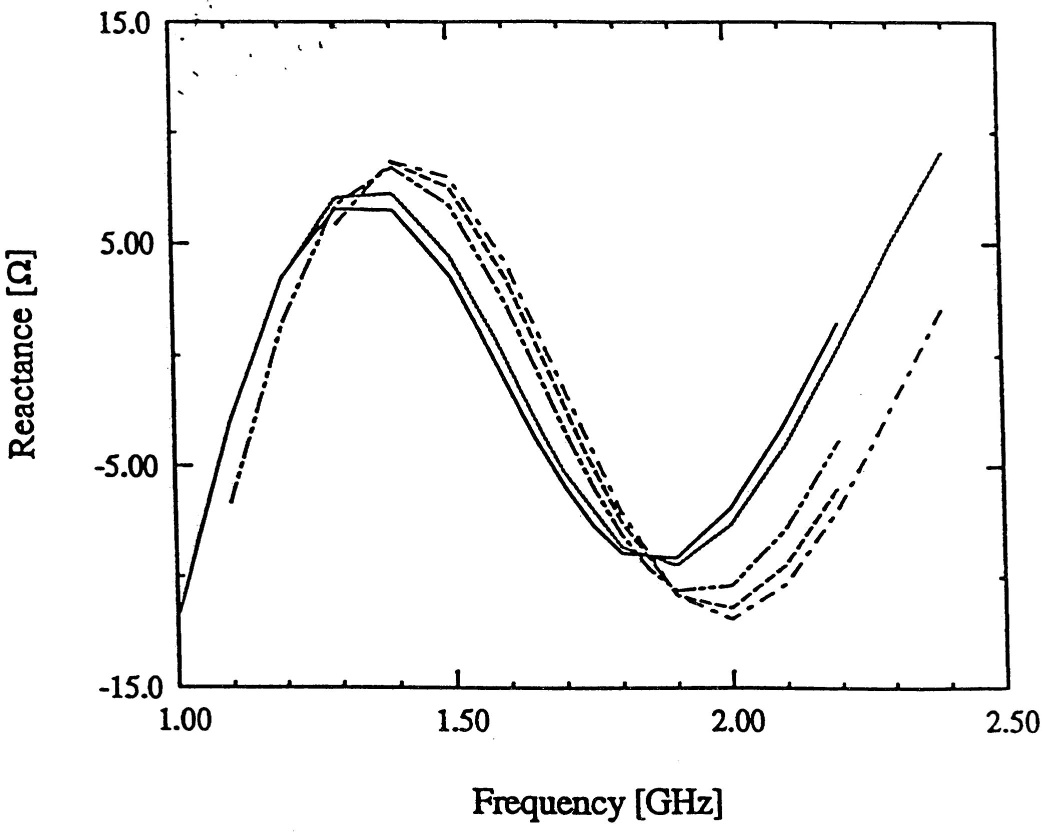


Figure 20: Input impedance of the large separation folded slot as a function of frequency

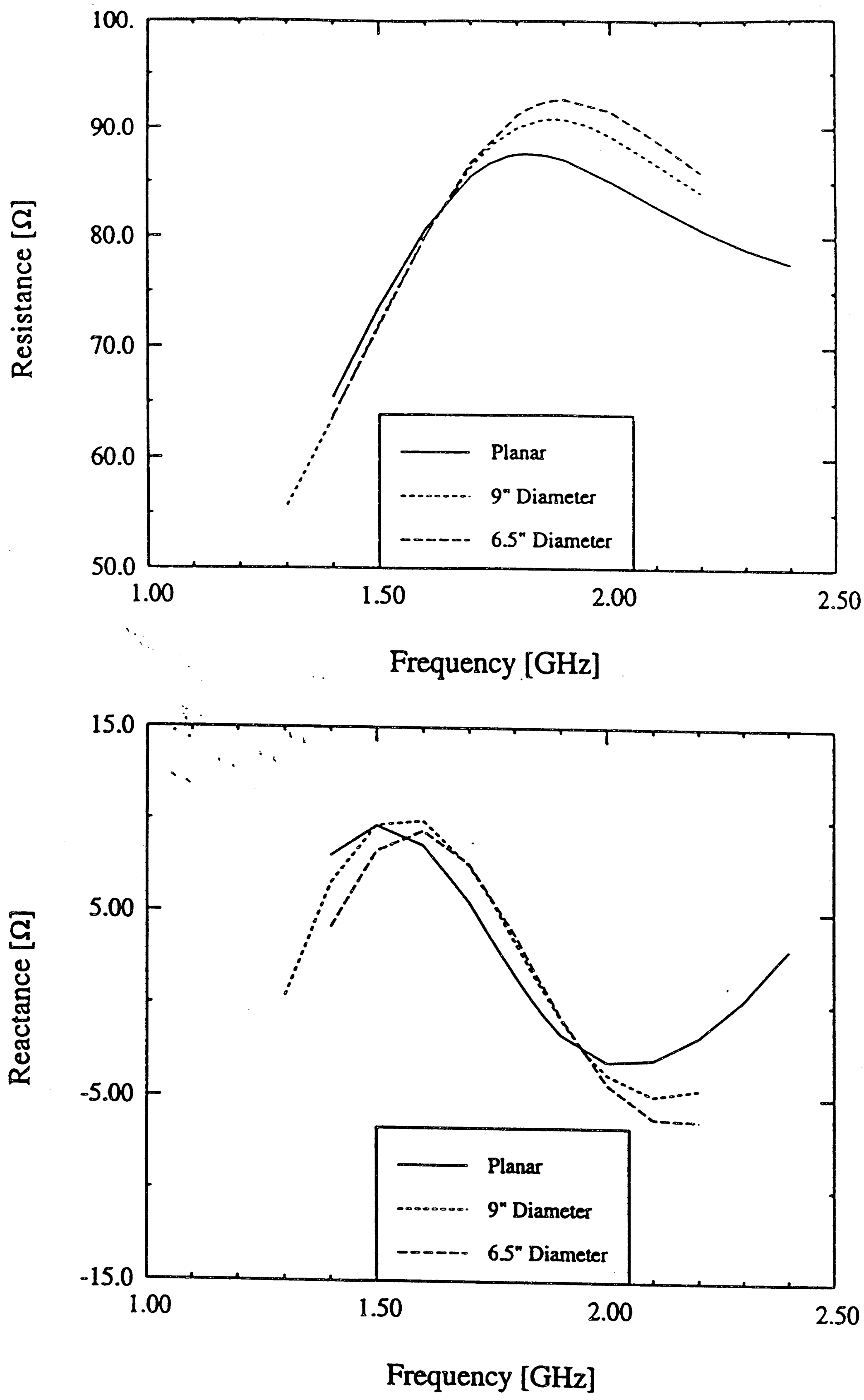


Figure 21: Input impedance of the narrow separation folded slot as a function of frequency

9 Appendix A

The transcript of a typical session with FEMA_CYL while finding the slot impedance as a function of frequency, is given below :

```
|||||||||||||||||||||||||||||||||||||||||||||||||||||||
|                                                     |
|                      FEMA_CYL                       |
|                                                     |
| A program for antenna arrays on metallic cylinders  |
|                                                     |
|                 Radiation Laboratory                |
|                University of Michigan               |
|                                                     |
| Copyright:   The Regents of the                     |
|              University of Michigan     (1993)      |
|                                                     |
|||||||||||||||||||||||||||||||||||||||||||||||||||||||


||||||||||||||||||||||||||||||||||||||||||||||
|            Memory Demand                   |
||||||||||||||||||||||||||||||||||||||||||||||

Integer arrays requires:   22.04013     MBytes
Real    arrays requires:  2.0800000E-04 MBytes
Complex arrays requires:   24.44435     MBytes

ESTIMATED TOTAL MEMORY DEMAND >   46.48469     Mbytes


Do you wish to run:
                    1) Preprocessor
                    2) FEM-BI
                    3) Impedance aperture
                    0) Exit
```

```
1

 Performing initialization, please wait....

 Enter radius of cylinder (cm):
8.125
 Enter array size (phi,z) in (deg,cm):
127.9600571 13.31976
 Enter center of array (phi,z) in (deg,cm):
0 0
 Enter number of grid points in (phi,z) direction
48 70

 Discretization:
                  deltaPhi =     2.722554     deg
                  deltaZ   =    0.1930400     cm

 Enter number of cavities in phi,z directions
1 1

 Enter number of nodes per cavity (phi,z):
48 70


         3360 surface nodes have been generated...
 The node numbering has the following pattern

 SINGLE CAVITY:

   ^
   |   21   22   23   24   25
   |   16   17   18   19   20
   z   11   12   13   14   15
   |    6    7    8    9   10
   |    1    2    3    4    5
   ---------- phi ---------->
```

```
 if for example 25 nodes were specified.
 where node 13 is the center point.


 Now specify which other nodes are either:
             metallic
                or
             resistive

 All surface nodes metal or resistive (1=yes):
0
Are the nodes substrate nodes (1=yes):
0
 Enter number of metallic patches:
5
 Enter row,column of lower left corner of
 the patch on uniform grid for patch:            1
0 0
 Enter number of unknowns(edges) for each
 dimension (phi,z):
47 32
 Enter row,column of lower left corner of
 the patch on uniform grid for patch:            2
32 0
 Enter number of unknowns(edges) for each
 dimension (phi,z):
16 5
 Enter row,column of lower left corner of
 the patch on uniform grid for patch:            3
32 31
 Enter number of unknowns(edges) for each
 dimension (phi,z):
16 5
 Enter row,column of lower left corner of
 the patch on uniform grid for patch:            4
37 0
 Enter number of unknowns(edges) for each
```

```
 dimension (phi,z):
47 32
 Enter row,column of lower left corner of
 the patch on uniform grid for patch:           5
33 17
 Enter number of unknowns(edges) for each
 dimension (phi,z):
13 3
 Enter number of substrate layers(INTEGER):
7

 Generating sub-surface nodes....
 Enter layer            1 thickness (cm):
.0254
 Enter layer            2 thickness (cm):
1.125
 Enter layer            3 thickness (cm):
1.125
 Enter layer            4 thickness (cm):
1.125
 Enter layer            5 thickness (cm):
1.125
 Enter layer            6 thickness (cm):
1.125
 Enter layer            7 thickness (cm):
1.125

 Do you want to save this geometry (1=yes):
1
 Enter FEMA_CYL filename:
a8125.cyl
 Do you wish to run:
                    1) Preprocessor
                    2) FEM-BI
                    3) Impedance aperture
                    0) Exit
 2
```

```
 Performing initialization, please wait....

 Enter FEMA_CYL filename:
a_8125.cyl
 Reading FEMA_CYL file: a_8125.cyl

 Is this geometry quasi-planar (0=no, 1=yes):
0
 Material Parameter Specification....
 Is the material filling constant (1=yes,0=no)?
0
 Each layer of elements constant (1=yes,0=no)?
0
 Well, each element must be individually entered...
 Entry by keyboard or file (1=key,0=file)?
0
 Material file must have structure:
 Re[epsilon] Im[epsilon] Re[mu] Im[mu]
 There must be at least        22701lines.
 (one line per element)

 Enter material filename:
mat_spec_file

 Checking dimension allocations...

 Number of Boundary Integral Unknowns:          36
 Total number of UNKNOWNS:       60152

Enter tolerance, minimum and maximum iterations:
.01 2 10000
Do you wish to monitor convergence (0=no,1-yes)?
1
 Do you want:  0 = no preconditioning, 1 = diagonal?
1
 Do you want to compute:
```

```
      0 = RCS/Pattern, 1 = Zin, 2 = Freq. Sweep?
2
 Enter Zin filename:
slotzin
 Enter Frequency sweep data filename:
freqsweep
 Enter observation type:
                          0) Backscatter
                          1) Bistatic
                          2) Radiation
2
 Enter start,stop, and increment azmuth angles [deg]:
0 0 1

 Enter start,stop,and increment elevation angles [deg]:
90 90 1

 Enter ouput RCS filename [<= 40 characters]:
junk
 ||||||||||||||||||||||||||||||||||||||||
 |     PROBE FEED INFORMATION           |
 ||||||||||||||||||||||||||||||||||||||||

 Enter number of feeds:
1
 Enter feed direction (1=rho, 2=phi, 3=z):
3
 Enter feed location (rho,phi) in (cm,deg):
8.124999 0
 Enter center point of feed (cm):
-.57912
 Enter layer number of feed <=:            7
1
 Enter mag,phase of probe current (amp,deg):
1 0
 ||||||||||||||||||||||||||||||||||||||||
 |     IMPEDANCE LOAD INFORMATION       |
```

```
 ||||||||||||||||||||||||||||||||||||||||

 Enter number of loads:
0
 Enter start,stop and increment freq. (GHz):
1.4 2.4 .1
Do you wish to run:
                     1) Preprocessor
                     2) FEM-BI
                     3) Impedance aperture
                     0) Exit
0
```