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User's Manual for CBS3DS Version 1.0

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CONTENTS

1. INTRODUCTION

CBS3DS is a computer code written in FORTRAN 77 to compute the backscattering radar cross section of cavity backed apertures in infinite ground plane (fig. 1)[1] and slots in thick infinite ground plane (fig. 2)[2]. CBS3DS implements the hybrid Finite Element Method (FEM) and Method of Moments (MoM) techniques [1,2,3]. This code uses the tetrahedral elements, with vector edge basis functions for FEM in the volume of the cavity/slot and the triangular elements with the basis functions similar to that described in [1], for MoM at the apertures. By virtue of FEM, this code can handle any arbitrarily shaped three-dimensional cavities filled with inhomogeneous lossy materials, and due to MoM, the apertures can be of any arbitrary shape. The basic theory implemented in the code is given in Appendix 1.

The User's Manual is written to make the user acquainted with the operation of the code. The user is assumed to be familiar with the FORTRAN 77 language and the operating environment of the computers, the code is intended to run. The organization of the Mannual is as follows. Section 2 explains the installation requirements. The operation of the code is given in detail in Section 3. Two example runs, one for the cavity backed aperture in an infinite ground plane and the other for the slot in a thick ground plane, are demonstrated in Section 4. Some test cases are presented in Section 5 to show the flexibility of the code. The test cases were run by the authors to validate the code. Users are encouraged to try these cases to get themselves acquainted with the code.

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1. This will be referred to as Case I.
2. This will be referred to as Case II.

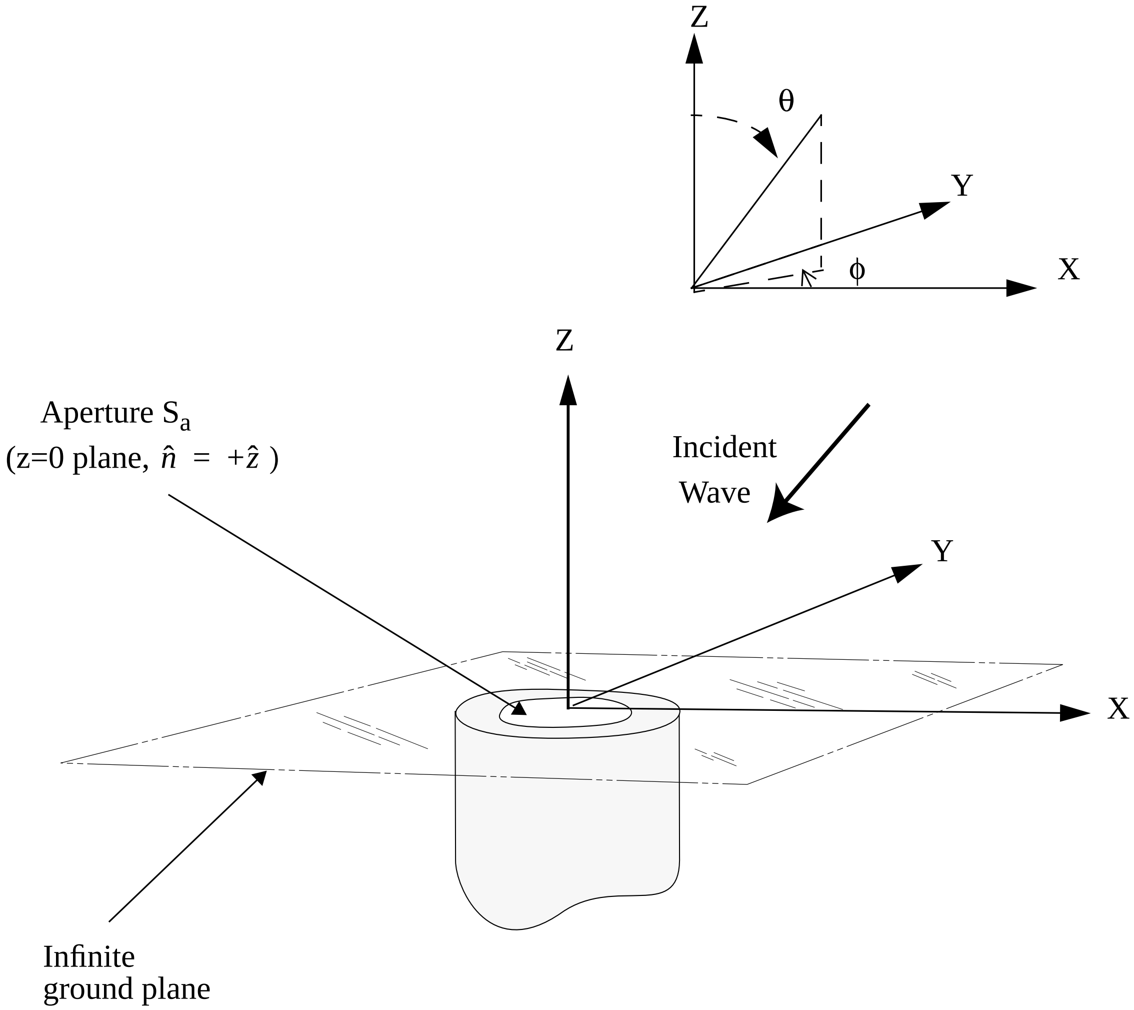


Figure 1 Cavity backed aperture in an infinite ground plane (Case I)

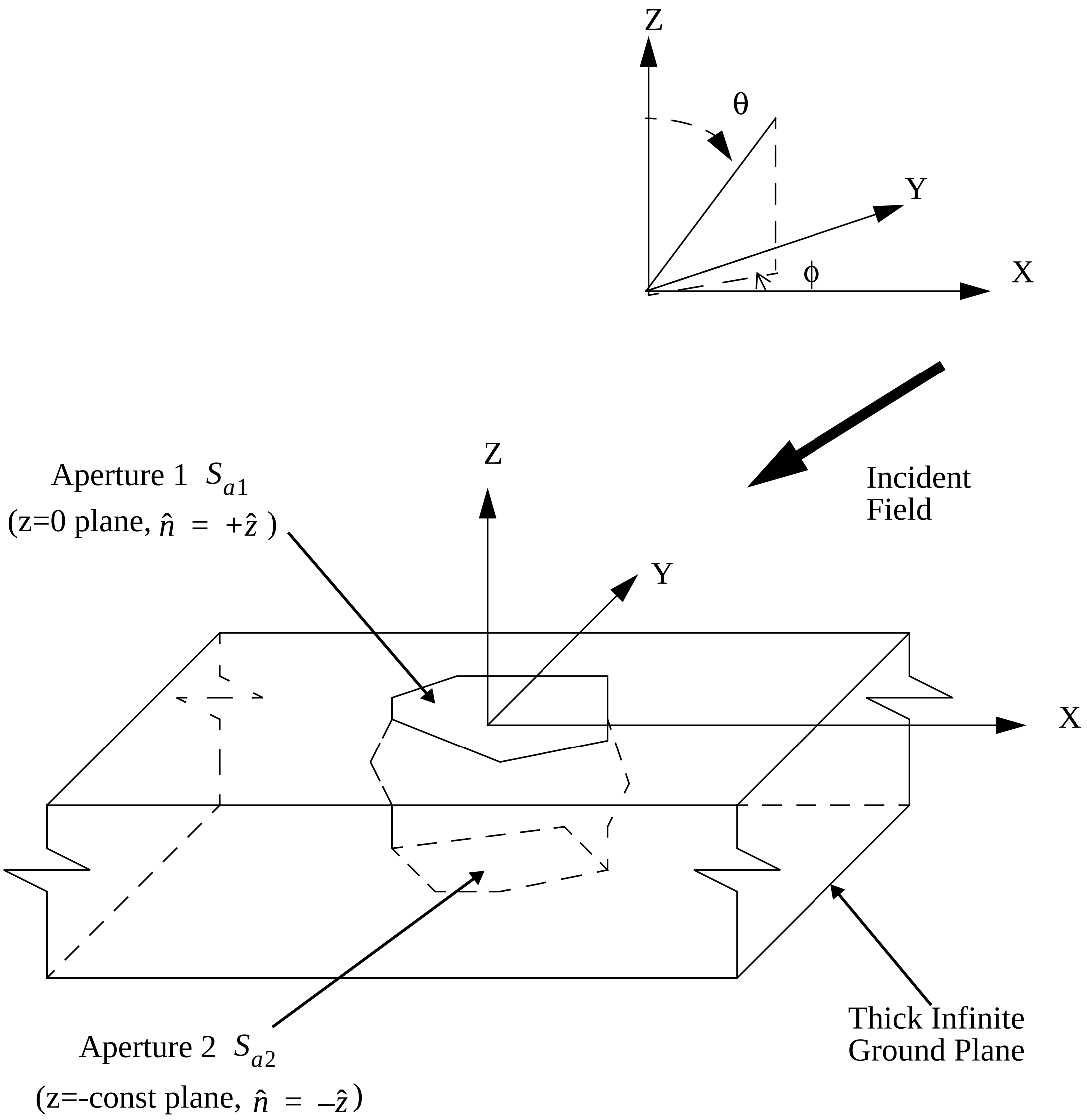


Figure 2 Slot in a thick infinite ground plane (Case II)

2.0 INSTALLATION OF THE CODE

The distribution disk of CBS3DS is 3.5" floppy disk formatted for IBM compatible PCs. It contains a file named `cbs3ds_t.z`. This file has to be transferred to any UNIX machine via `ftp` using binary mode. On the UNIX machine, use the following commands to get all the files.

```
mv cbs3ds_t.z cbs3ds.tar.Z
uncompress cbs3ds.tar.Z
tar -xvf cbs3ds.tar
```

This creates a directory `CBS3DS-1.0`, which in turn contains the subdirectories, `CBS3DS` (source files for the main code), `PRE_CBS3DS` (source files for preprocessing code), `Example1` and `Example2.` As the code is written in FORTRAN 77, with no particular computer in mind, the source codes in these directories should compile on any computer architecture without any problem. The code was successfully complied on SUN, SGI, and CONVEX machines, and the compilation can be done by using `make_sun, make_sgi,` and `make_convex` files for the respective machines. The complete listing of the directories in the distribution disk is given in Appendix 2.

3.0 OPERATION OF THE CODE

The computation of backscattering from a specific geometry with CBS3DS is a multi-stage process as illustrated in figure 3. The geometry of the problem has to be constructed with the help of any commercial Computer Aided Design (CAD) package. In our case, we used COSMOS/M[4] as our geometry modeler and meshing tool. As the infinite ground plane is accounted for in the formulation of the theory, only the cavity or the slot geometry need to be constructed using the geometry modeler. It can also be noted that by identifying the aperture 2 in Case II as a PEC surface, Case II turns out to be Case I. The code treats Case I as the problem with aperture 1 only and Case II as the problem with aperture 1 and aperture 2. As CBS3DS uses edge based basis functions, the nodal information supplied by most of the meshing routines, cannot be readily used. Hence, a preprocessor PRE_CBS3DS is written to convert the nodal based data into edge based data and then is given as input to CBS3DS. For the convenience of the users, who use different CAD/meshing packages other than COSMOS/M, PRE_CBS3DS accepts the nodal based data in a generic format also. The procedures involved for using COSMOS/M input data file or generic input data file is explained below.

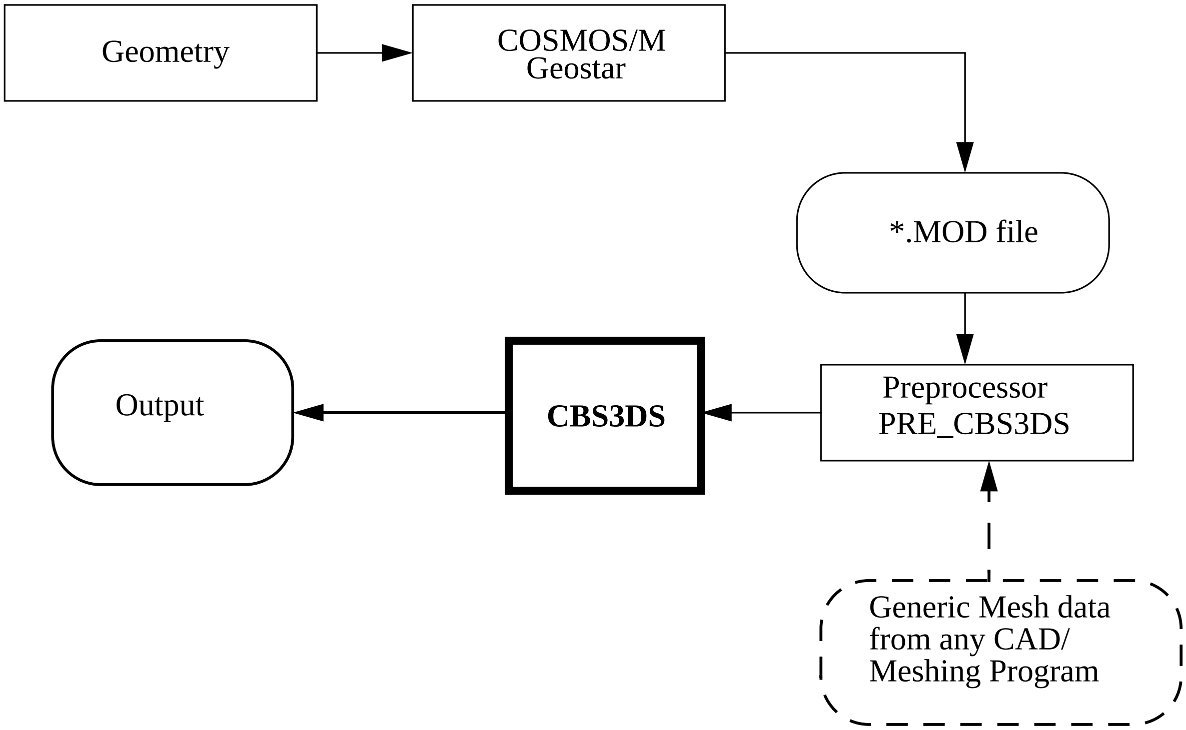


Figure 3 Flow chart showing the various steps involved in computing scattering using CBS3DS

With the help of COSMOS/M, the geometry is constructed and meshed with tetrahedral elements. The user is assumed to be familiar with COSMOS/M package and its features. Once the mesh is generated, one needs to identify the following to impose proper boundary conditions:

(a) tetrahedral elements with different material parameters[1]

(b) elements on PEC surfaces

(c) elements on aperture surfaces

This is done using the available features in COSMOS/M. A sample *.SES file of COSMOS/M which illustrates these features is given in Appendix 3. Finally *.MOD file is generated with mesh information required. PRE_CBS3DS accepts the *.MOD file as input and generates the required edge based data.

For the users, who can do geometry modelling and meshing of the model with any other CAD package, the nodal based information is required to be placed in a file *`problem`*`.PIN`, where *`problem`* is the name of the problem under consideration. The format required for `*.PIN` file is given in Appendix 4. Note that all the dimensions of the geometry are assumed to be in centimeters.

The PRE_CBS3DS code gives the following prompts:

```
pre_cbs3ds
Give the problem name:
```

The problem name is the user defined name for the particular problem under consideration.

---

[1] COSMOS/M has a feature by which it can group tetrahedral elements with different material properties into different groups. For a generic file input, user has to specify the material property index for each tetrahedral element to indicate its material property group(see Appendix 4).

```
COSMOS file (1) or GENERIC (2) file?
```

If you are using *.MOD file from COSMOS/M give 1, or using the generic input data file explained above, give 2.

PRE_CBS3DS generates the following files with required edge based information.

(a) *problem*`_nodal.dat` - Node coordinates and the node numbers for each element

(b) *problem*`_edges.dat` - Information on edges, such as nodes connecting each edge etc.

(c) *problem*`_surfed.dat` - Information on number of edges on each surface

(d) *problem*`_surfel1.dat` - Information on edges on Aperture 1

(e) *problem*`_surfel2.dat` - Information on edges on Aperture 2

(f) *problem*`.POUT` - General information on the mesh.

The files (a) to (e) are used as input for CBS3DS. Users need not interact or modify the above files.

After PRE_CBS3DS is run, all but one input data file required for CBS3DS are ready. CBS3DS expects to find *problem*`.MAT` file which contains the material constants information required for the volume elements. The format of the *problem*`.MAT` is as given below:

N_g,	Maximum number of material groups
ε_{r1}, μ_{r1}	Complex relative permittivity, Complex relative permeability for
ε_{r2}, μ_{r2}	material groups 1, 2, 3, ..., N_g
.	
.	
ε_{rN_g}, μ_{rN_g}	

In the PRE_CBS3DS, all the terahedral elements are given the material group index. The material parameters given in *problem*`.MAT` are read into CBS3DS and the proper material parameters are assigned to each tetrahedral element according to its material property index.

Once the *problem*.`MAT` is ready, CBS3DS code can be run.

The CBS3DS code gives the following prompts:

```
cbs3ds
```

```
Give the problem name :
```

This name should be the same as given for PRE_CBS3DS

```
Frequency (GHZ) :
```

This is the frequency of operation. If the dimensions of the problem are in wavelengths, frequency should be specified as 30 GHz as CBS3DS assumes that all dimensions are in centimeters.

```
Give alpha=0 for H-polarization
Give alpha=90 degs for E-polarization
```

This is to specify the polarization of the incident plane wave.

```
Plane of incidence-
Give 1 for fixed phi and phi(degs)
     2 for fixed theta and theta(degs)
```

This specifies the angle of incidence for the incident wave. Backscatter calculations can be done at a constant ϕ-plane or at a constant θ-plane by choosing either 1 or 2 and giving the value of ϕ or θ at the plane of interest respectively.

```
Give angle of incidence-
start,end,increment (degs) :
```

This specifies range of angles for which backscatter calculations are to be performed. For a constant ϕ-plane, these are values of θ and for constant θ-plane these are values of ϕ.

CBS3DS generates the file *problem*.`OUT`, which contains some information on CPU times for matrix generation, matrix fill and the backscatter values in dB/λ^2 units. CBS3DS also generates another file *problem*_`bicgd.DAT` which contains information on number of iterations and error tolerance used for biconjugate gradient algorithm.

4.0 SAMPLE RUNS

Two example runs are illustrated in this section. One is a cavity backed aperture in an infinite ground plane and the other is a slot in a thick infinite ground plane.

Example 1 : An air-filled rectangular cavity in infinite ground plane

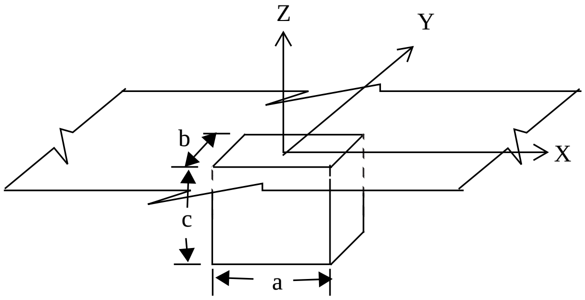


Figure 4 An air-filled rectangular cavity in an infinite ground plane.

A rectangular air-filled cavity with length 0.7λ, width 0.1λ, and depth 1.73λ with the aperture opening into an infinite ground plane as shown in figure 4 is considered. Backscatter pattern was computed in a constant θ-plane at $\theta = 40^o$ for $\phi = 0^0$to 90^o with H-polarized ($\alpha = 0^o$) incident wave.

First the PRE_CBS3DS

```
cjr@sirius:{25} pre_cbs3ds
Give the problem name :
Example1
COSMOS file(1) or GENERIC(2) file ?
1
 Opening file :Example1.MOD
 Read from *.MOD file :
 Nodes=  307
 Elements=  771
 Elements on PECs=  590
 Elements on Aper 1=  14
 Elements on Aper 2=  0
```

```
Read the following data
Nodes=  307
Elements=  771
Elements on surface 1=  14
Elements on surface 2=  0

Forming the edges !!! Be patient !!!

**************************************************
Number of nodes=  307
Number of elements=  771
Number of total edges=  1379
Number of edges on surface 0(pec)=  893
Number of edges on surface 1(MoM1)=  29
Number of edges on surface 2(MoM2)=  0
Max number of maetrial groups=  1

Order of the FEM-MoM matrix =  486
Order of the MoM-1 matrix   =  13
Order of the MoM-2 matrix   =  0
**************************************************
```

The `Example1.MAT` file for this problem is given below:

```
1
(1.0,0.0) (1.0,0.0)
```

And then CBS3DS :

```
cjr@sirius:{28} cbs3ds
Give the problem name :
Example1
Frequency (GHZ) :
30.0

Give alpha=0 for H-polarization
Give alpha=90 degs for E-polarization
0

Plane of incidence-
Give 1 for fixed phi and phi(degs)
     2 for fixed theta and theta(degs)
2 40
```

```
Give angle of incidence-
start,end,increment (degs) :
0 90 5
 Reading the input !!
Finished reading the data

***************************************

BACKSCATTERING CALCULATION FOR CAVITY BACKED APERTURE

Frequency (GHz)            =    30.0000
Order of the FEM-MoM matrix=  486
H-Polarization-Alpha(deg)=  0.
Sweep through phi : theta =  40

*-------------------------------------*

Computing the MoM matrix for Aperture 1
Be patient !!!!

Time to fill FEM matrix(secs)  =   0.950000
Time to fill MoM-1 matrix(secs)=    12.1300

Non zero entries in matrix A (before MoM)-with symmetry=  2085
Non zero entries in matrix A (after MoM)-with symmetry=  2151

*-------------------------------------*

  Ang(deg)    SigHH        SigHE               Time(secs)-BiCGD

     0      -53.6379      -49.5830        2.8900
     5      -40.2321      -21.0658        3.6500
    10      -28.0119      -15.0938        3.3600
    15      -20.8940      -11.6697        3.3800
    20      -15.8666       -9.3225        3.9800
    25      -11.9828       -7.5972        3.8100
    30       -8.8294       -6.2996        3.6900
    35       -6.1919       -5.3348        3.8100
    40       -3.9463       -4.6554        3.8200
    45       -2.0167       -4.2419        3.8100
    50       -0.3546       -4.0935        3.4700
    55        1.0717       -4.2261        3.8600
    60        2.2829       -4.6734        3.8700
    65        3.2932       -5.4948        3.8500
    70        4.1111       -6.7940        3.8100
    75        4.7428       -8.7655        3.8100
```

```
    80         5.1919      -11.8392        3.2800
    85         5.4604      -17.3337        3.7400
    90         5.5497      -39.9934        3.0700

*****************************************
```

The complete session of this run on a SUN-Sparcserver 630MP along with all the files is kept in the directory `/CBS3DS-1.0/Example1.`

Example 2: Slot in a thick infinite ground plane

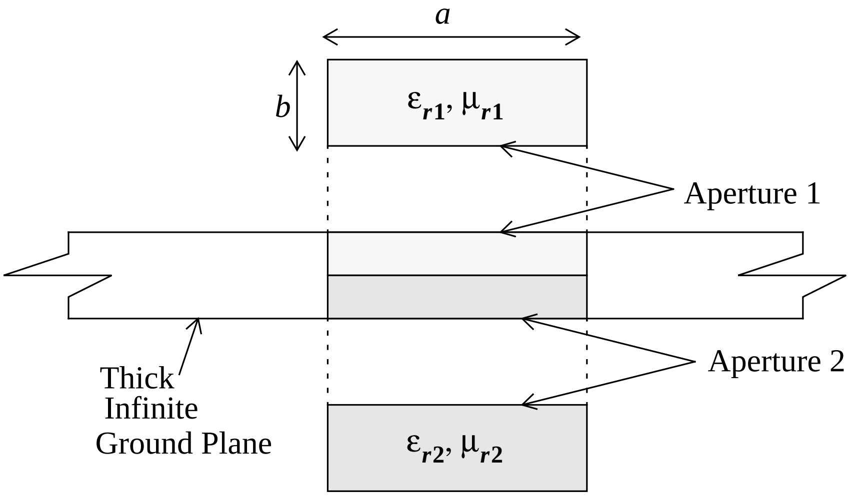


Figure 5 Slot filled with two dielectric layers in a thick infinite ground plane.

The geometry of the slot is shown in figure 5 with $a = 1.2\lambda$, $b = 0.25\lambda$ and thickness of 0.25λ. The slot is filled with different dielectric layers (top layer $\varepsilon_{r1} = 2$, $\mu_{r1} = 1.2$ and 0.125λ thick; bottom layer $\varepsilon_{r2} = 3$, $\mu_{r2} = 1$ and 0.125λ thick). Backscatter pattern was computed in a constant ϕ-plane at $\phi = 0^o$ for $\theta = 0^0$to 90^o with H-polarized ($\alpha = 0^o$) incident wave.

First the PRE_CBS3DS

```
cjr@sirius:{22} pre_cbs3ds
```

```
Give the problem name :
Example2
COSMOS file(1) or GENERIC(2) file ?
1
 Opening file :Example2.MOD
 Read from *.MOD file :
 Nodes=  434
 Elements=  1626
 Elements on PECs=  304
 Elements on Aper 1=  120
 Elements on Aper 2=  120

Read the following data
Nodes=  434
Elements=  1626
Elements on surface 1=  120
Elements on surface 2=  120

Forming the edges !!! Be patient !!!

**************************************************
Number of nodes=  434
Number of elements=  1626
Number of total edges=  2331
Number of edges on surface 0(pec)=  494
Number of edges on surface 1(MoM1)=  199
Number of edges on surface 2(MoM2)=  199
Max number of maetrial groups=  2

Order of the FEM-MoM matrix =  1837
Order of the MoM-1 matrix   =  161
Order of the MoM-2 matrix   =  161
**************************************************
```

The `Example2.MAT` file for this problem is given below:

```
2
(2.0,0.0) (1.2,0.0)
(3.0,0.0) (1.0,0.0)
```

And then CBS3DS

```
cjr@sirius:{25} cbs3ds
Give the problem name :
Example2
Frequency (GHZ) :
30.0
```

```
Give alpha=0 for H-polarization
Give alpha=90 degs for E-polarization
0

Plane of incidence-
Give 1 for fixed phi and phi(degs)
     2 for fixed theta and theta(degs)
1 0
Give angle of incidence-
start,end,increment (degs) :
0 90 5
 Reading the input !!
Finished reading the data

***************************************

BACKSCATTERING CALCULATION FOR SLOT IN THICK GROUND PLANE

Frequency (GHz)            =    30.0000
Order of the FEM-MoM matrix=  1837
H-Polarization-Alpha(deg)=  0.
Sweep through theta : phi =  0

*-------------------------------------*
Computing the MoM matrix for Aperture 1
Be patient !!!!


Computing the MoM matrix for Aperture 2
Be patient !!!!

Time to fill FEM matrix(secs)  =    2.40000
Time to fill MoM-1 matrix(secs)=    828.560
Time to fill MoM-2 matrix(secs)=    828.350

Non zero entries in matrix A (before MoM)-with symmetry=  13590
Non zero entries in matrix A (after MoM)-with symmetry=  38780

*-------------------------------------*

  Ang(deg)    SigHH        SigHE              Time(secs)-BiCGD

     0       -1.5195      -42.0374       69.7401
     5       -2.1431      -42.1244       71.7200
    10       -4.1160      -42.4920       70.9600
```

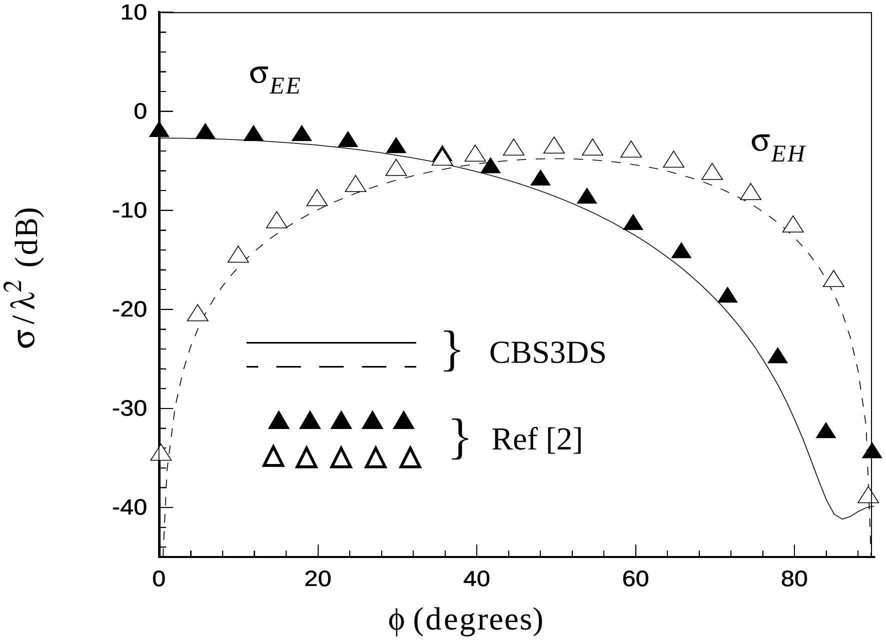
```
    15       -7.9053      -42.7986       74.4701
    20      -15.3351      -42.9657       76.7300
    25      -31.4777      -43.0722       71.7001
    30      -15.8668      -43.2740       78.1699
    35      -12.9846      -43.6691       78.5300
    40      -12.9388      -44.2616       77.8000
    45      -14.7240      -44.9835       78.3899
    50      -18.4151      -45.8319       78.3999
    55      -25.3653      -46.8286      160.5701
    60      -32.0941      -48.0989       80.3098
    65      -23.7822      -49.7361       76.2600
    70      -20.1292      -51.8684       78.4602
    75      -18.3268      -54.6038       94.4998
    80      -17.3968      -58.3723       76.5500
    85      -16.9519      -64.5815       79.0701
    90      -16.8204     -190.6529       76.7700

****************************************
```

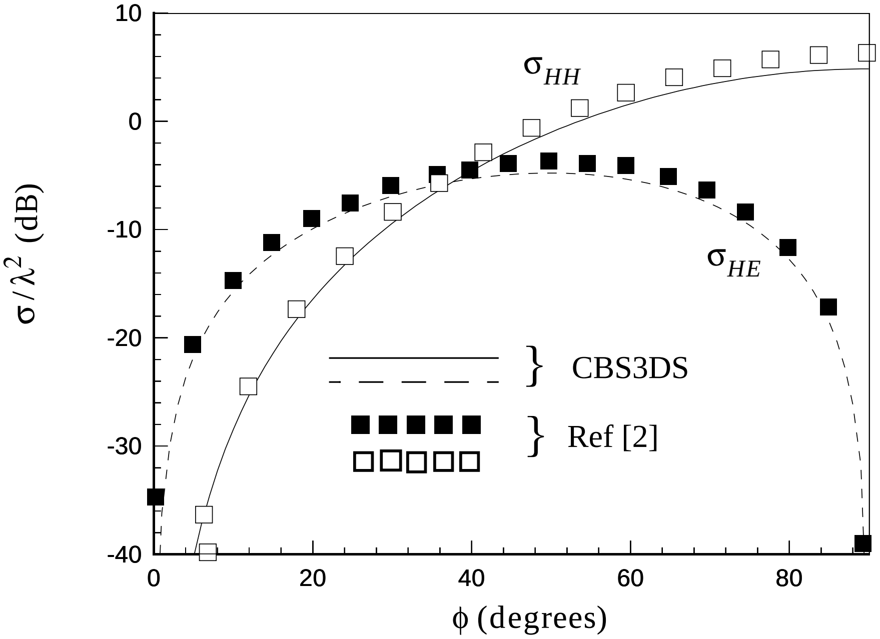
The complete session of this run on a SUN-Sparcserver 630MP along with all the files is kept in the directory `CBS3DS-1.0/Example2`.

5.0 TEST CASES

Test Case 1: Air-filled rectangular cavity in an infinite ground plane. (Example 1 in Section 4)

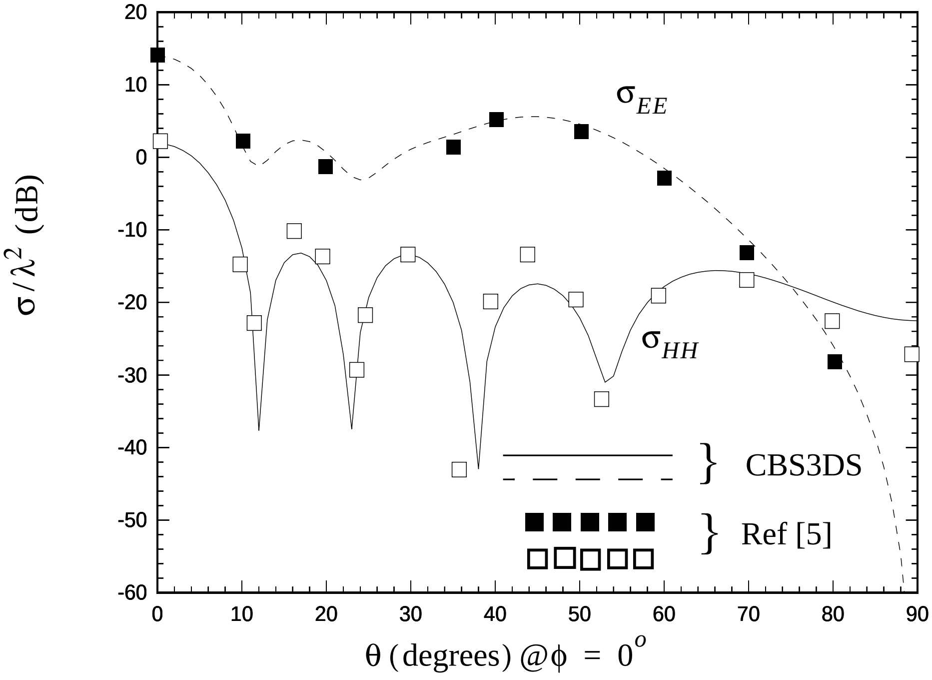
a=0.7λ, b=0.1λ, c=1.73λ, θ=40°

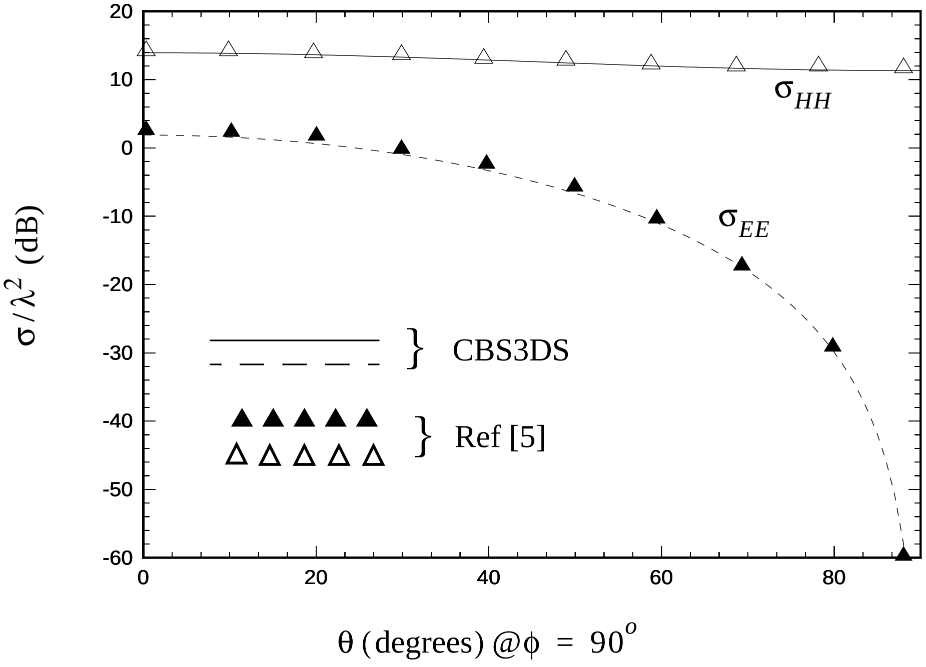




Test Case 2: Air-filled rectangular cavity in an infinite ground plane. (figure 4)

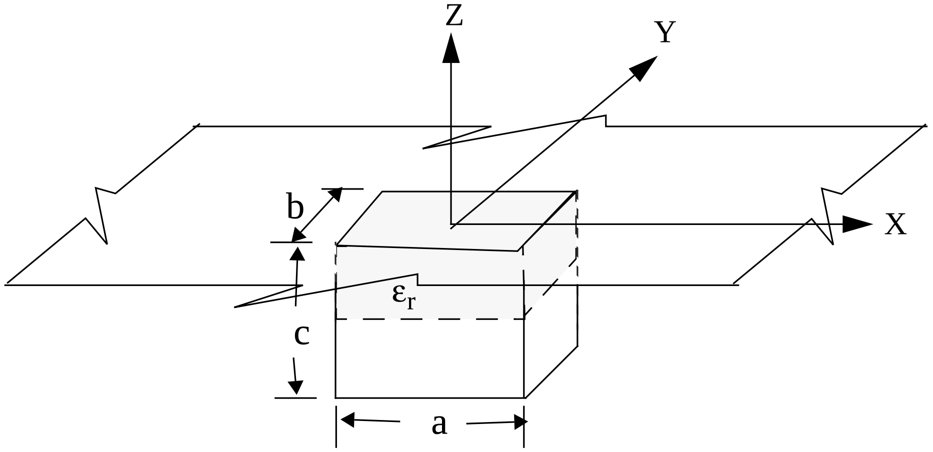
a=2.5λ, b=0.25λ, c=0.25λ

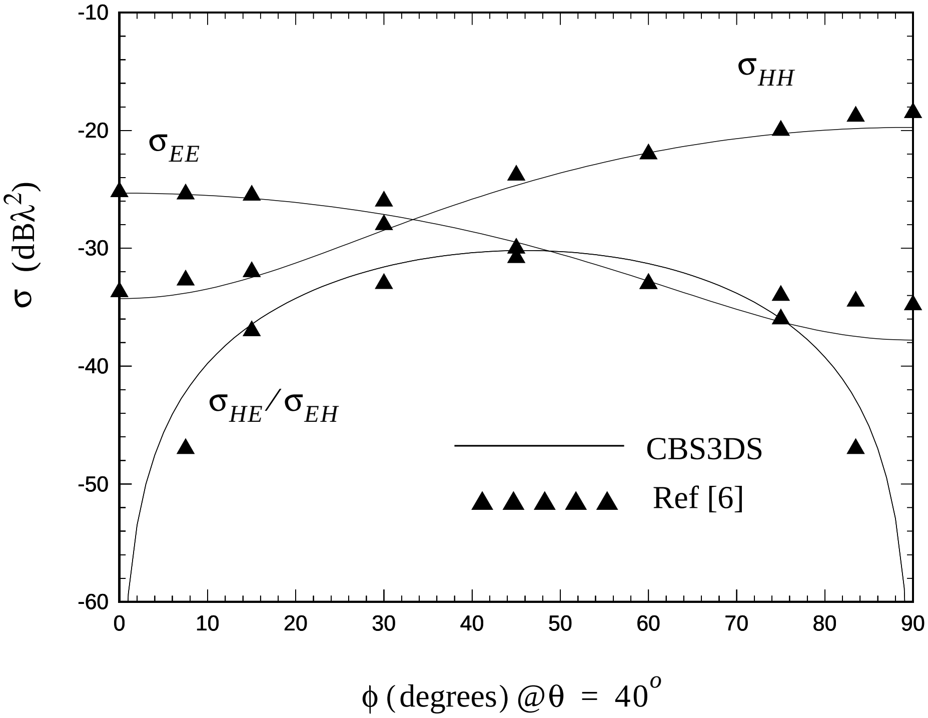




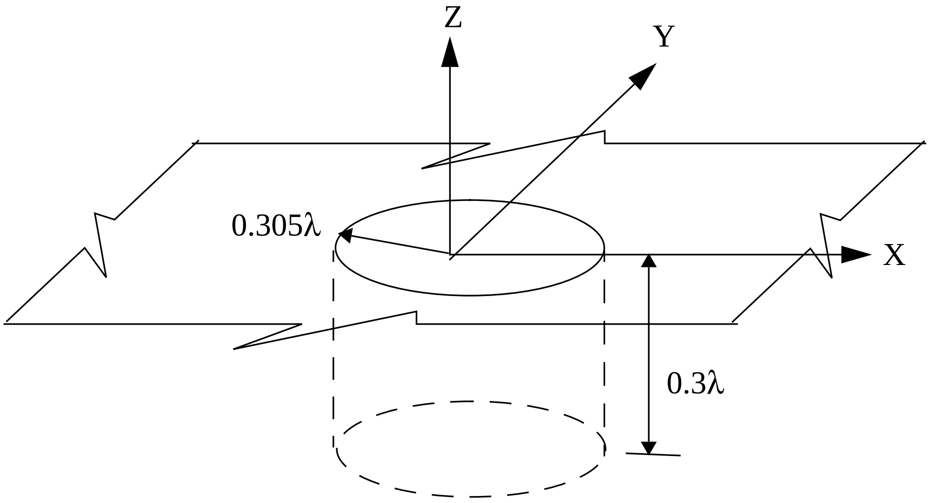
Test Case 3: A partly filled rectangular cavity in an infinite ground plane

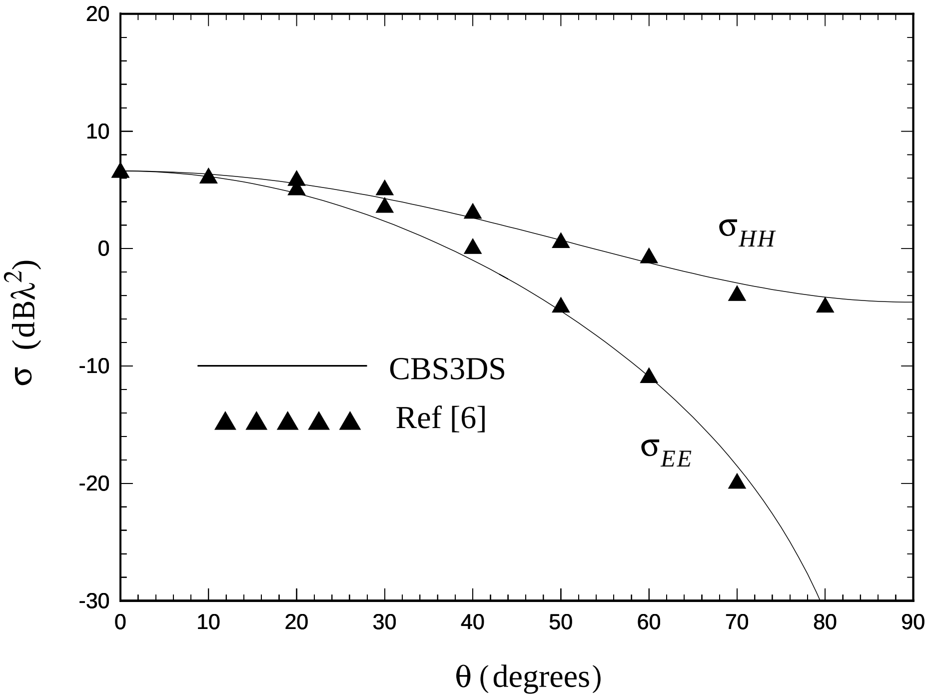
a=0.3λ, b=0.1λ, c=0.6λ, ε_r=2-j2 and thickness of the dielectric layer = 0.2λ





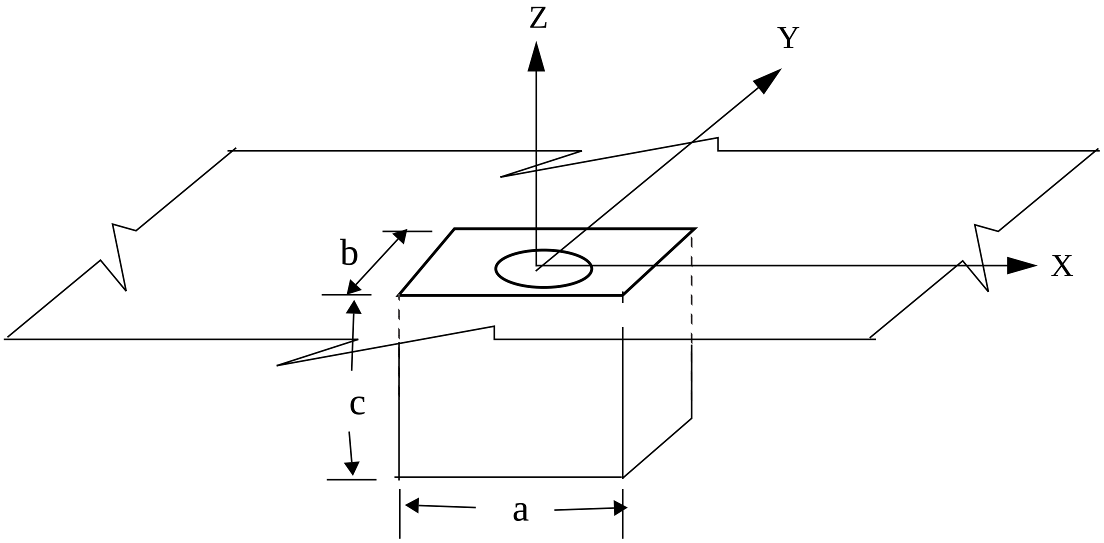
Test Case 4: Air-filled circular cavity in an infinite ground plane

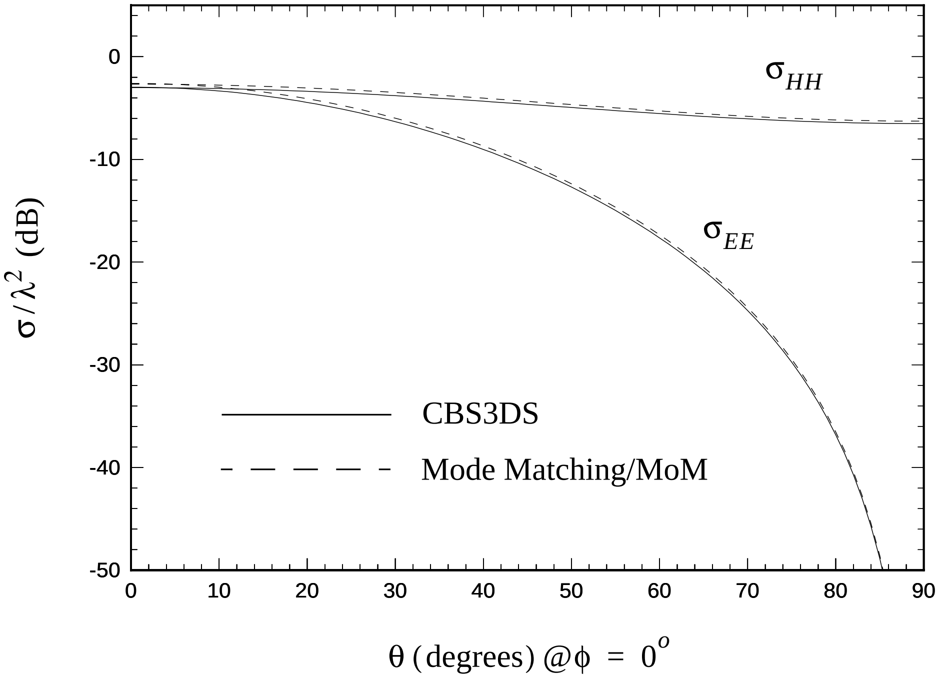




Test Case 5: Air-filled rectangular cavity with a circular aperture

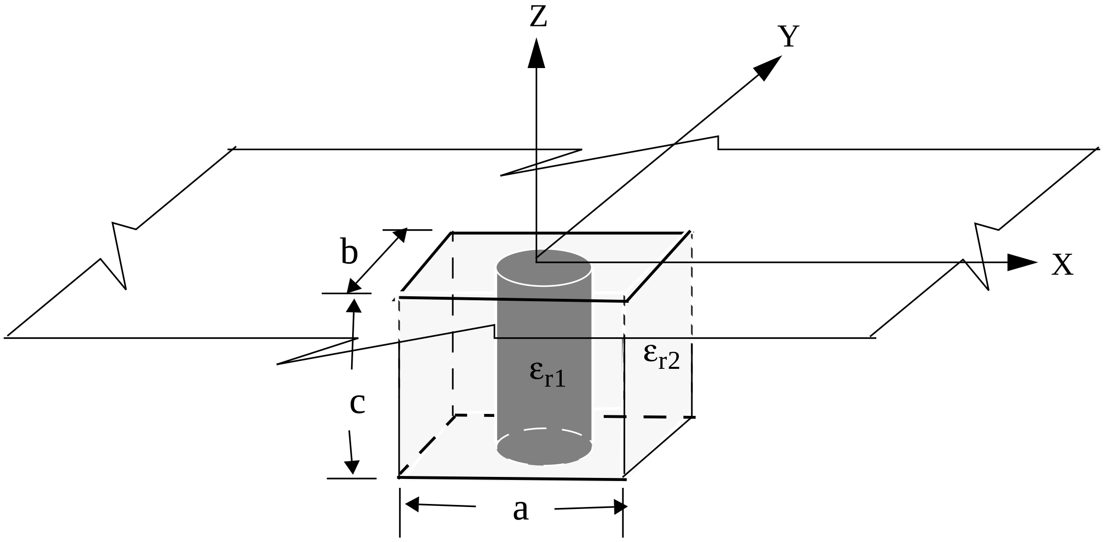
$a=0.5\lambda$, $b=0.5\lambda$, $c=0.3\lambda$, and the radius of the circular aperture $= 0.2\lambda$

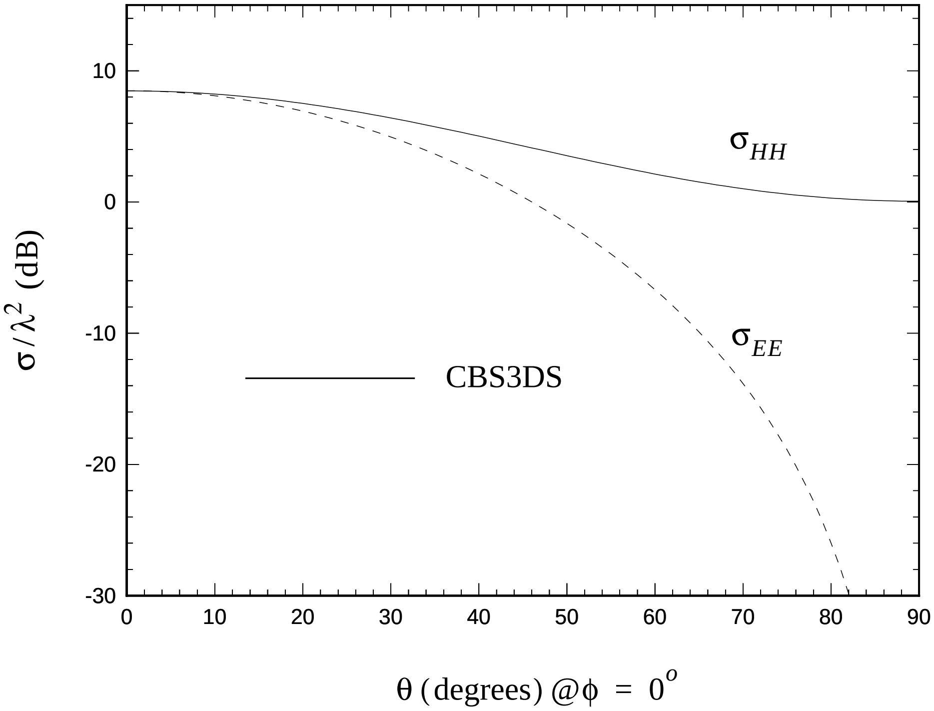




Test Case 6: **Inhomogeneously filled cavity in an infinite ground plane**

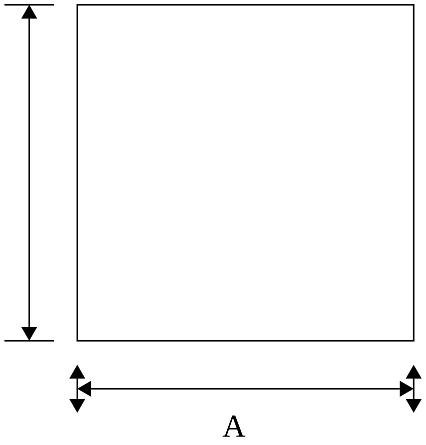
a=0.5λ, b=0.5λ, c=0.3λ, ε_{r1}=2.0, ε_{r2}=1.5 and the radius of the inner dielectric = 0.2λ

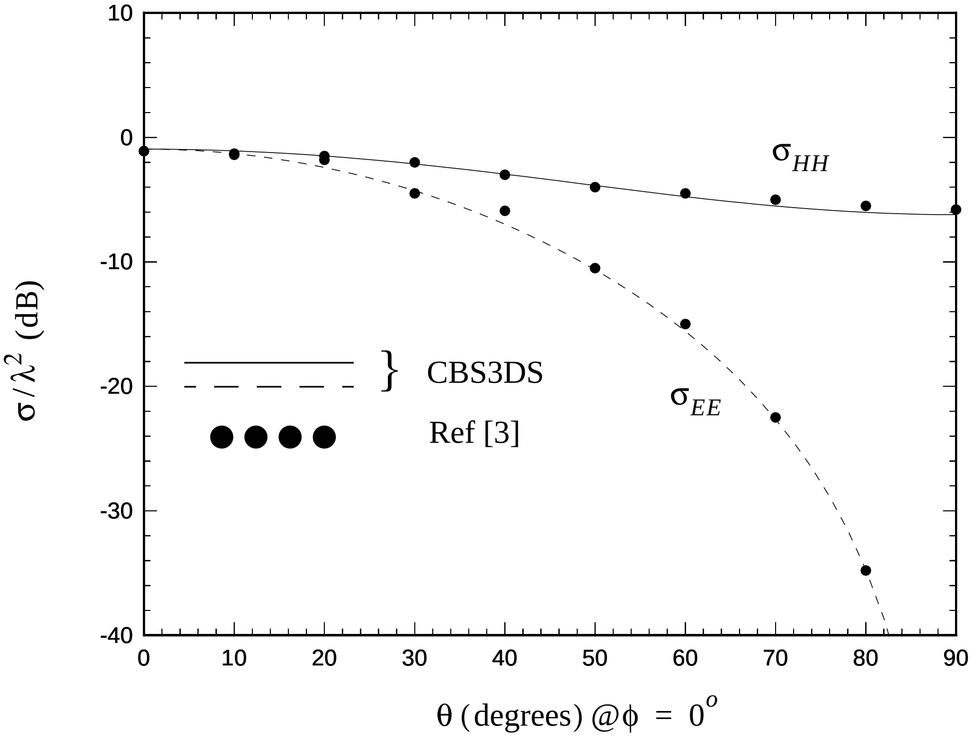




Test Case 7: **Air-filled square slot in a thick ground plane**

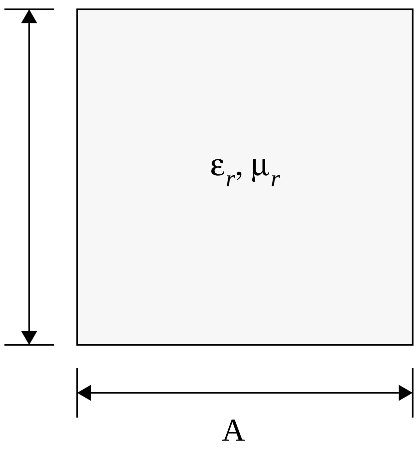
A=0.4λ, B=0.4λ and thickness = 0.25λ

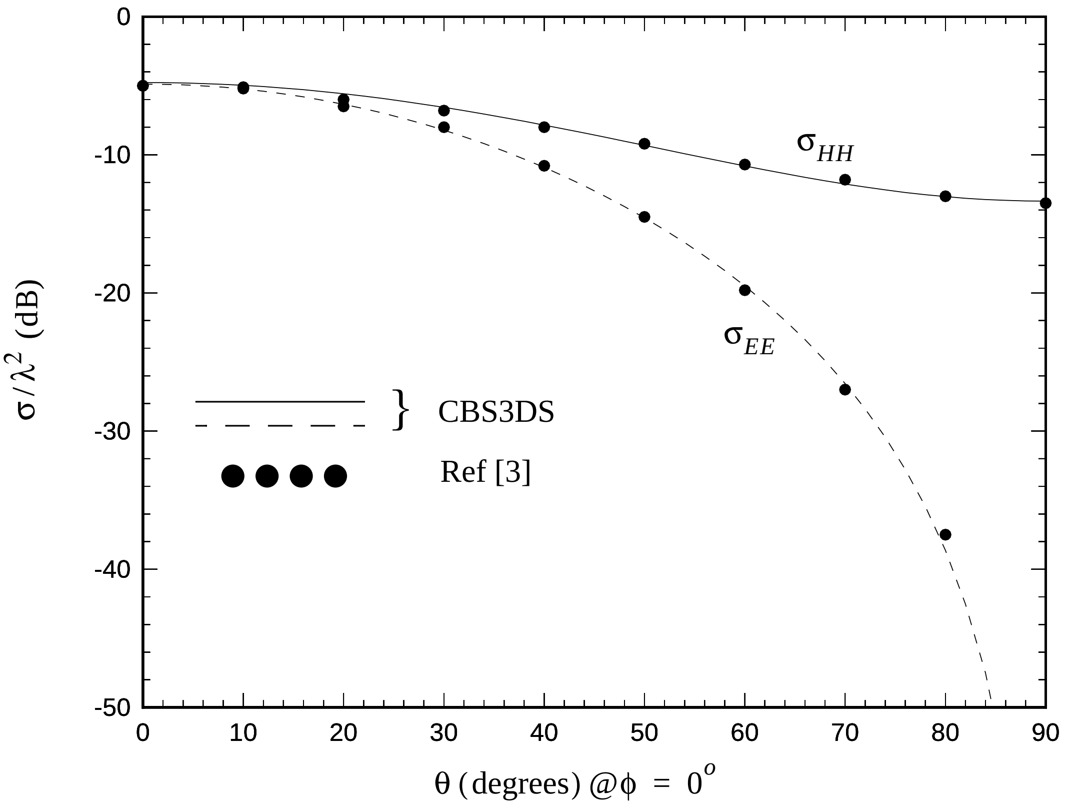




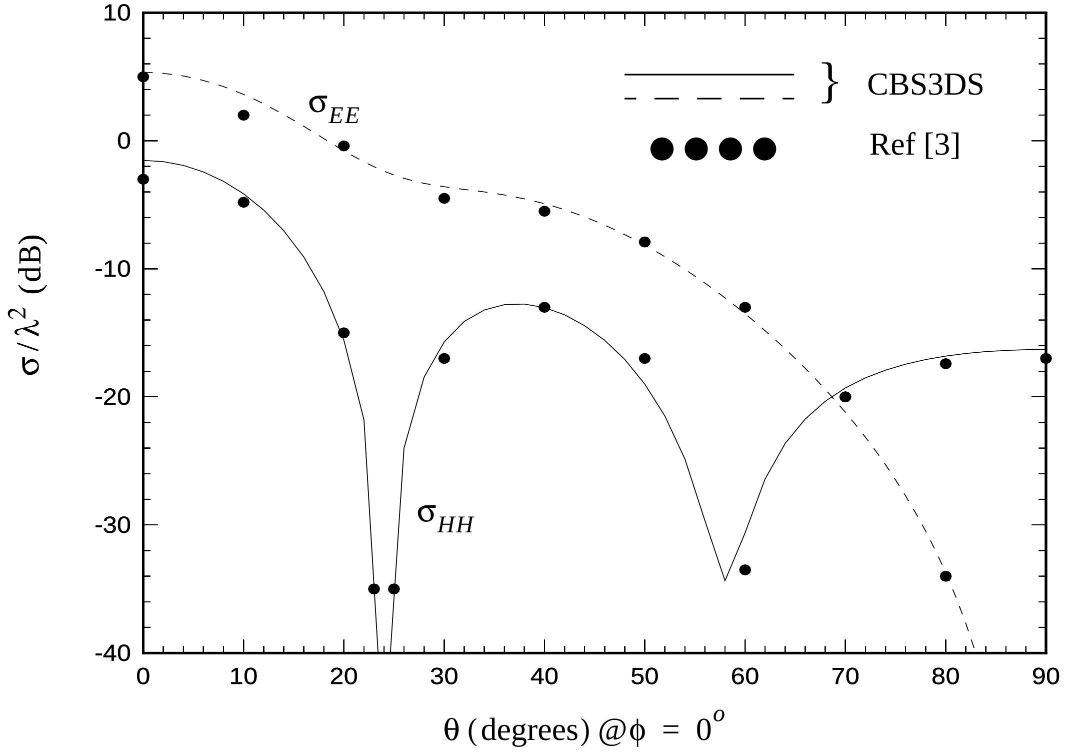
Test Case 8: Square slot in a thick ground plane filled with lossy material.

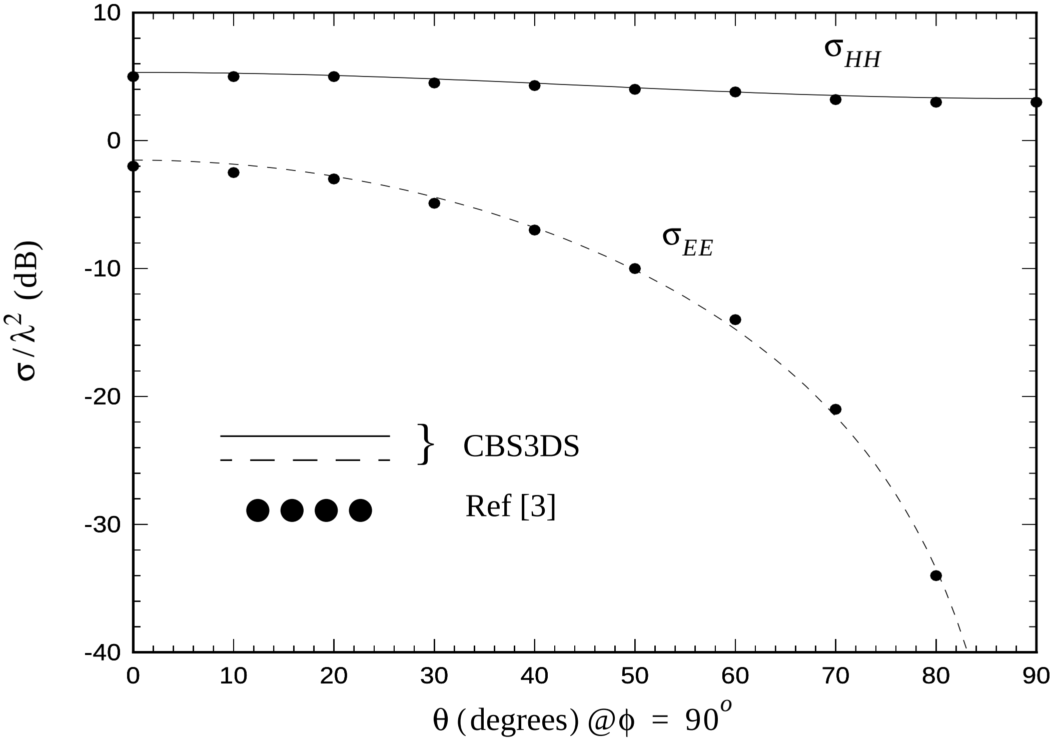
A=0.4λ, B=0.4λ and thickness = 0.25λ; $\varepsilon_r = 2 - j$ and $\mu_r = 1.2 - j0.1$





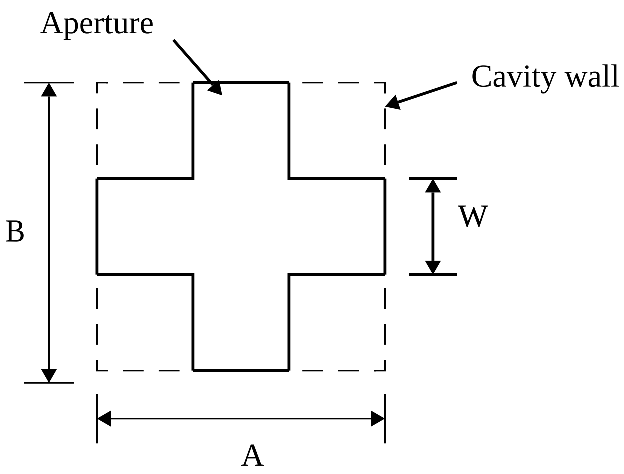
Test Case 9: Rectangular slot in a thick ground plane filled with layered dielectric layers (Example 2 in Section 4)

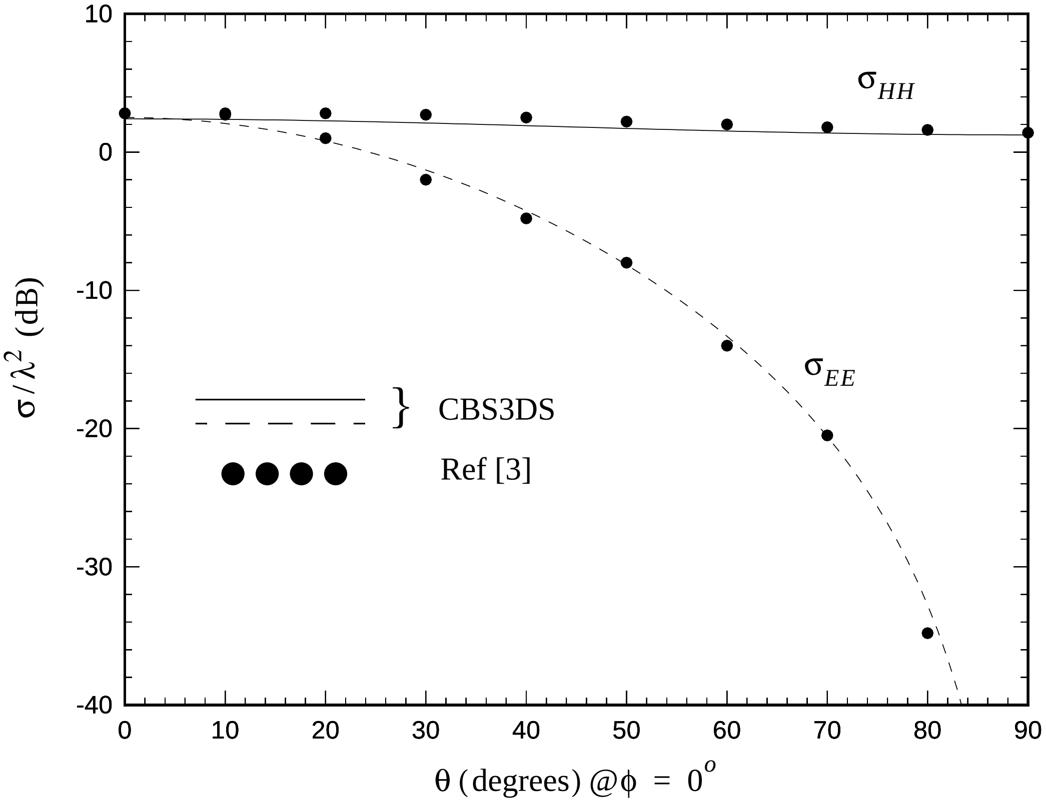




Test Case 10: Air-filled square cavity in a thick ground plane with a cross-shaped aperture its upper and bottom walls.

A=B=0.5λ, thickness=0.25λ and W=0.125λ.





6.0 CONCLUDING REMARKS

The usage of CBS3DS code is demonstrated so that the user can get acquainted with the details of using the code with minimum possible effort. The flexibility of the code is demonstrated in a wide variety of test cases presented in Section 5. As no software can be bug free, CBS3DS is expected to have hidden bugs which can only be detected by the repeated use of the code for a variety of geometries. Any comments or bug reports should be sent to the authors. As the reported bugs are fixed and more features added to the code, future versions will be released. Information on future versions of the code can be obtained from

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Appendix 1

Theory for CBS3DS

This appendix is intended to give a brief description of the theory behind the code. For more details, consult ref [1,2,3]. The geometries of the two problems are illustrated in figures 1 and 2 respectively. In figure 1, the cavity backed aperture in an infinite ground plane is illustrated. The infinite ground plane is assumed to be in z=0 plane. This will be referred to as Case I. In figure 2, the slot in thick infinite ground plane is shown and will be referred to as Case II. Considering that the these geometries are illuminated by a plane wave, the electric field in side the volume of the cavity/slot satisfies the source free vector wave equation:

$$\nabla\times\left(\frac{1}{\mu_r}\nabla\times\vec{E}\right)-k_o^2\varepsilon_r\vec{E} = 0 \tag{1}$$

where μ_r is the relative permeability and ε_r is the relative permittivity of the medium.

To facilitate the suitable solution of the partial differential equation in (1) via FEM, equation (1) is multiplied with a vector testing function $\vec{T}$ and integrated over the volume of the cavity. Further, by doing some mathematical manipulations, equation (1) can be written in the form [1, equation 11].

$$\begin{aligned}\iiint_V \frac{1}{\mu_r}\left(\nabla\times\vec{T}\right)\bullet\left(\nabla\times\vec{E}\right)dv-k_o^2\varepsilon_r\iiint_V\vec{T}\bullet\vec{E}dv-j\omega\mu_o\iint_{S_a}\left(\vec{T}\times\hat{n}\right)\bullet\vec{H}_{scat}ds \\ = 2j\omega\mu_o\iint_{S_a}\left(\vec{T}\times\hat{n}\right)\bullet\vec{H}_{inc}ds\end{aligned} \tag{2}$$

for Case I and

$$\iiint_V \frac{1}{\mu_r}\left(\nabla\times\vec{T}\right)\bullet\left(\nabla\times\vec{E}\right)dv - k_o^2\varepsilon_r\iiint_V \vec{T}\bullet\vec{E}dv$$

$$-j\omega\mu_o\iint_{S_{a1}}\left(\vec{T}\times\hat{n}\right)\bullet\vec{H}_{scat}ds - j\omega\mu_o\iint_{S_{a2}}\left(\vec{T}\times\hat{n}\right)\bullet\vec{H}_{scat}ds$$

$$= \quad 2j\omega\mu_o\iint_{S_{a1}}\left(\vec{T}\times\hat{n}\right)\bullet\vec{H}_{inc}ds \qquad (3)$$

for Case II.

At this point, the problem can be divided into three parts, the first part involving the discretization and evaluation of volume integrals on the left hand side of equation (4) and the second part involving the discretization and evaluation of the surface integral over S_a in equation (2) and over S_{a1} and S_{a2} in equation (3). The third part involves the surface integral due to the incident plane wave. The volume integral is evaluated by discretizing the volume of the cavity with tetrahedral elements and evaluating the integral over the volume of each tetrahedral element. These element volume integral contributions are added together over all tetrahedral elements to form a sparse matrix. The second part is evaluated over the surface of the aperture(s). The discretization of the volume of the cavity into tetrahedral elements automatically discretizes the aperture(s) surface into triangular elements. Assuming the current basis functions similar to that described in [1], an integral equation is formed, which contributes to the dense part of the system matrix. Image theory is used to account for the presence of the infinite ground plane. The third integral evaluated over the aperture S_a/S_{a1} forms the excitation column matrix.

By adding the contributions from FEM and MoM integrals and evaluating the excitation vector equation (3) can be written in matrix form as

$$\left[A\right]\{e\} = \{b\} \qquad (4)$$

where [A] is a partly sparse (due to FEM), partly dense (due to MoM) symmetric matrix. The column vector {e} is the unknown coefficient vector to be solved, {b} is the excitation vector. Due to the sparsity and symmetry of matrix A, only the nonzero elements of one half of the matrix (upper half or lower half including the diagonal) are stored to minimize the memory demand. A diagonally preconditioned biconjugate gradient algorithm is used to efficiently solve the equation(4).

Once the electric field $\vec{E}$ is found and hence the magnetic current $\vec{M}$ on the aperture S_a/S_{a1}, the far zone scattered magnetic field can be computed.

$$\vec{H}_{scat}(\vec{r})\Big|_{r\to\infty} = -\frac{jk_o}{\eta_o}\frac{e^{-jk_o r}}{2\pi r}\int\int_{S_a/S_{a1}} (\hat{\theta}\hat{\theta}+\hat{\phi}\hat{\phi})\bullet\vec{M}(x,y)\,e^{jk_o\sin\theta(x\cos\phi+y\sin\phi)}\,dxdy \qquad (5)$$

where (r, θ, ϕ) are the usual spherical coordinates of the observation point. The scattering cross section is then given by

$$\sigma = \lim_{r\to\infty} 4\pi r^2 \frac{\left|\vec{H}_{scat}(\vec{r})\right|^2}{\left|\vec{H}_{inc}(\vec{r})\right|^2} \qquad (6)$$

where

$$\left|\vec{H}_{scat}(\vec{r})\right|^2 = \left|H_{\theta s}\right|^2 + \left|H_{\phi s}\right|^2$$

$$\left|\vec{H}_{inc}(\vec{r})\right|^2 = \left|H_{\theta i}\right|^2 + \left|H_{\phi i}\right|^2$$

The total scattering cross section is defined by equation (5). However, in most of the measurements, either E-polarized or H-polarized waves are transmitted and the E-polarized and H-polarized scattered far fields are measured separately. In such cases, the scattering cross section may be defined as

(7)

$$\sigma_{HH} = \lim_{r \to \infty} 4\pi r^2 \frac{|H_{\phi s}|^2}{|H_{\phi i}|^2} \tag{8}$$

$$\sigma_{HE} = \lim_{r \to \infty} 4\pi r^2 \frac{|H_{\theta s}|^2}{|H_{\phi i}|^2} \tag{9}$$

$$\sigma_{EE} = \lim_{r \to \infty} 4\pi r^2 \frac{|H_{\theta s}|^2}{|H_{\theta i}|^2} \tag{10}$$

$$\sigma_{EH} = \lim_{r \to \infty} 4\pi r^2 \frac{|H_{\phi s}|^2}{|H_{\theta i}|^2} \tag{11}$$

Appendix 2

Listing of the Distribution Disk

```
/CBS3DS-1.0

total 5
drwxr-xr-x  2 cjr            512 Aug 22 14:47 CBS3DS/
drwxr-xr-x  2 cjr            512 Aug 22 14:44 Example1/
drwxr-xr-x  2 cjr            512 Aug 22 15:38 Example2/
drwxr-xr-x  2 cjr            512 Aug 22 14:20 PRE_CBS3DS/
-rw-r--r--  1 cjr            287 Aug 22 14:46 README

/CBS3DS-1.0/PRE_CBS3DS

total 33
-rw-r--r--  1 cjr           6651 Aug 16 08:38 cosmos2fem.f
-rw-r--r--  1 cjr           5322 Aug 15 19:13 edge.f
-rw-r--r--  1 cjr            629 Aug 22 12:55 make_convex
-rw-r--r--  1 cjr            304 Aug 22 11:28 make_sgi
-rw-r--r--  1 cjr            293 Aug 14 10:35 make_sun
-rw-r--r--  1 cjr           1556 Aug 15 19:12 meshin.f
-rw-r--r--  1 cjr           1658 Aug 15 19:10 param0
-rw-r--r--  1 cjr           1403 Aug 15 19:19 pmax.f
-rw-r--r--  1 cjr           8130 Aug 16 10:20 pre_cbs3ds.f
-rw-r--r--  1 cjr           2984 Aug 15 19:15 surfel.f

/CBS3DS-1.0/CBS3DS

total 85
-rw-r--r--  1 cjr           2875 Aug 19 22:37 analy.f
-rw-r--r--  1 cjr           4644 Aug 19 22:40 basis.f
-rw-r--r--  1 cjr           3398 Aug 19 22:55 bicgd.f
-rw-r--r--  1 cjr          16122 Aug 19 21:56 cbs3ds.f
-rw-r--r--  1 cjr           2252 Aug 19 22:10 elembd.f
-rw-r--r--  1 cjr           3602 Aug 19 22:06 elmatr.f
-rw-r--r--  1 cjr           2311 Aug 19 22:14 excit.f
-rw-r--r--  1 cjr           2907 Aug 19 22:42 fourierxy.f
-rw-r--r--  1 cjr            731 Aug 22 14:47 make_convex
-rw-r--r--  1 cjr            407 Aug 22 12:33 make_sgi
-rw-r--r--  1 cjr            421 Aug 16 10:40 make_sun
-rw-r--r--  1 cjr           3321 Aug 14 12:41 param
-rw-r--r--  1 cjr           2477 Aug 19 22:16 scatter.f
```

```
-rw-r--r--  1 cjr         1021 Aug 19 22:54 second.f
-rw-r--r--  1 cjr         3970 Aug 19 22:35 triang.f
-rw-r--r--  1 cjr         4363 Aug 19 22:31 triang0.f
-rw-r--r--  1 cjr         3069 Aug 11 17:12 triang01.f
-rw-r--r--  1 cjr         3444 Aug 19 22:33 triang011.f
-rw-r--r--  1 cjr         1505 Aug 19 22:46 unorm.f
-rw-r--r--  1 cjr          888 Aug 19 22:48 vcross.f
-rw-r--r--  1 cjr         6151 Aug 19 22:24 zmatrix1.f
-rw-r--r--  1 cjr         6153 Aug 19 22:23 zmatrix2.f

/CBS3DS-1.0/Example1

total 750
-rw-r--r--  1 cjr           22 Aug 17 08:50 Example1.MAT
-rw-r--r--  1 cjr        53407 Aug 17 09:59 Example1.MOD
-rw-r--r--  1 cjr         1610 Aug 19 23:00 Example1.OUT
-rw-r--r--  1 cjr        41555 Aug 17 16:15 Example1.PIN
-rw-r--r--  1 cjr          558 Aug 17 16:15 Example1.POUT
-rw-r--r--  1 cjr          354 Aug 17 09:58 Example1.SES
-rw-r--r--  1 cjr         1349 Aug 19 23:00 Example1_bicgd.DAT
-rw-r--r--  1 cjr       113313 Aug 17 16:15 Example1_edges.DAT
-rw-r--r--  1 cjr        29591 Aug 17 16:15 Example1_nodal.DAT
-rw-r--r--  1 cjr           30 Aug 17 16:15 Example1_surfed.DAT
-rw-r--r--  1 cjr         1300 Aug 17 16:15 Example1_surfel1.DAT
-rw-r--r--  1 cjr            4 Aug 17 16:15 Example1_surfel2.DAT
-rwxr-xr-x  1 cjr       270336 Aug 19 22:57 cbs3ds*
-rwxr-xr-x  1 cjr       221184 Aug 17 09:59 pre_cbs3ds*

/CBS3DS-1.0/Example2

total 1009
-rw-r--r--  1 cjr           42 Aug 17 14:47 Example2.MAT
-rw-r--r--  1 cjr        82071 Aug 17 14:46 Example2.MOD
-rw-r--r--  1 cjr         1660 Aug 19 22:53 Example2.OUT
-rw-r--r--  1 cjr        64347 Aug 17 14:46 Example2.PIN
-rw-r--r--  1 cjr          569 Aug 17 14:46 Example2.POUT
-rw-r--r--  1 cjr         1349 Aug 19 22:53 Example2_bicgd.DAT
-rw-r--r--  1 cjr       274685 Aug 17 14:46 Example2_edges.DAT
-rw-r--r--  1 cjr        53383 Aug 17 14:46 Example2_nodal.DAT
-rw-r--r--  1 cjr           37 Aug 17 14:46 Example2_surfed.DAT
-rw-r--r--  1 cjr        13331 Aug 17 14:46 Example2_surfel1.DAT
-rw-r--r--  1 cjr        14695 Aug 17 14:46 Example2_surfel2.DAT
-rwxr-xr-x  1 cjr       270336 Aug 19 21:58 cbs3ds*
-rwxr-xr-x  1 cjr       221184 Aug 17 14:46 pre_cbs3ds*
```

Appendix 3

Sample *.SES files of COSMOS/M

The geometry modelling and meshing can be accomplished by using COSMOS/M. A variety of commands are available to define geometries. The constructed geometry is meshed and the mesh data can be written to a file with the Modinput command. Dielectric materials are identified by using material property command before meshing the correponding part of the dielectric material. These are used as indices to tetrahedral elements, which will correspond to an entry in the `problem`.MAT file. Specifying the surfaces which are perfectly conducting, surfaces forming aperture 1 and aperture 2 is accomplished by enforcing a pressure boundary condition. Before the pressure condition is specified, a load condition has to be defined to indicate what type of surface is being specified. Load conditions of 1, 2, and 3 corresponds to perfectly conducting, aperture 1 and aperture 2 respectively.

The *.SES files for the sample runs presented in section 4 are given below.

Example 1:

```
C*
C*  COSMOS/M      Geostar V1.71
C*  Problem : Example1         Date :  8-17-95  Time :  9:23:39
C*
SF4CORD 1 -0.35 -0.05 0 0.35 -0.05 0 0.35 0.05 0 -0.35 0.05 0
SCALE 0
SFGEN 1 1 1 1 0 0 0 -1.73
SFEXTR 1 4 1 Z -1.73
SCALE 0
PH 1 SF 1 0.1 0.0001 1
PART 1 1 1
MA_PART 1 1 1 1 0 4
ACTSET LC 1
PSF 2 1 6 1 1 1 4
ACTSET LC 2
PSF 1 1 1 1 1 1 4
```

Example 2:

```
C*
C*  COSMOS/M      Geostar V1.71
C*  Problem : Example2         Date :  8-17-95  Time : 14:23:20
C*
SF4CORD 1 -0.6 -0.125 0 0.6 -0.125 0 0.6 0.125 0 -0.6 0.125 0
SCALE 0
SFGEN 1 1 1 1 0 0 0 -0.125
SFGEN 1 2 2 1 0 0 0 -0.125
SCALE 0
SFEXTR 1 4 1 Z -0.125
PH 1 SF 1 0.08 0.0001 1
SFEXTR 5 8 1 Z -0.125
SELINP SF 2 2 1 1
SELINP SF 3 3 1 1
SELINP SF 8 11 1 1
PH 2 SF 2 0.08 0.0001 1
INITSEL,SF,1,1
PART 1 1 1
PART 2 2 2
PARTPLOT 1 2 1
MPROP 1 PERMIT 1
MA_PART 1 1 1 1 0 4
MPROP 2 PERMIT 2
MA_PART 2 2 1 1 0 4
NMERGE 1 514 1 0.0001 0 0 0
NCOMPRESS 1 514
ACTSET LC 1
PSF 4 1 11 1 1 1 4
ACTSET LC 2
PSF 1 1 1 1 1 1 4
ACTSET LC 3
PSF 3 1 3 1 1 1 4
```

Appendix 4

Generic Input file format for PRE_CBS3DS

The following is the format of the generic input file (`problem.PIN`) to be supplied to PRE_CBS3DS with required nodal data.

N_n	● N_n: Number of nodes
N_e	● N_e : Number of trahedral elements
N_p	● N_p : Number of triangular elemets on PEC surfaces
N_{a1}	● N_{a1} : Number of triangular elements on Aperture 1
N_{a2}	● N_{a2} : Number of triangular elements on Aperture 2
N_g	● N_g : Maximum number of material groups
x_1, y_1, z_1 x_2, y_2, z_2 . . . . . $x_{N_p}, y_{N_p}, z_{N_p}$	Coordinates of the nodes 1,2,3...,N_n
$n_{11}, n_{21}, n_{31}, n_{41}, mg\ (1)$ $n_{12}, n_{22}, n_{32}, n_{42}, mg\ (2)$ $n_{1N_e}, n_{2N_e}, n_{3N_e}, n_{4N_e}, mg\ (N_e)$	Node numbers connecting each tetrahedral element 1, 2, 3, ...,N_e, and material group index number for each element

N_{e1} , n_{11}, n_{21}, n_{31} N_{e2} , n_{12}, n_{22}, n_{32} . . . $N_{eN_p}, n_{1N_p}, n_{2N_p}, n_{3N_p}$	Global number of the terahedral element with a triangular face on PEC surface (N_{e1}, N_{e2}, ..., N_{eN_p}) and three nodes connecting the triangular element
N_{e1} , n_{11}, n_{21}, n_{31} N_{e2}, n_{12}, n_{22}, n_{32} . . . . $N_{eN_{a1}}, n_{1N_{a1}}, n_{2N_{a1}}, n_{3N_{a1}}$	Global number of the terahedral element with a triangular face on aperture 1 (N_{e1}, N_{e2}, ..., $N_{eN_{a1}}$) and three nodes connecting the triangular element
N_{e1} , n_{11}, n_{21}, n_{31} N_{e2} , n_{12}, n_{22}, n_{32} . . . . . $N_{eN_{a2}}, n_{1N_{a2}}, n_{2N_{a2}}, n_{3N_{a2}}$	Global number of the terahedral element with a triangular face on aperture 2 (N_{e1}, N_{e2}, ..., $N_{eN_{a2}}$) and three nodes connecting the triangular element

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